

**Temperature-index modelling of runoff from a  
declining Alpine glacier**

**Jason David Bradley**

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declining Alpine glacier**

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## Abstract

The Gornera River, in the Pennine Alps, Switzerland, drains meltwater from Gornergletscher and its tributary glaciers, which contribute a large proportion of the runoff from this highly-glacierised basin. As the mass of ice has declined, recession of many smaller tributary glaciers has resulted in their separation from the trunk Gornergletscher. Declining glacier surface area might be expected to have reduced the ice melt contribution to runoff, and since the Little Ice Age Maximum extent, Gornergletscher has revealed a strong link between climatic change and ice-cover. Glaciers in the Swiss Alps have revealed a total ice volume loss since the 1870s of about  $13 \text{ km}^3$ . Approximately  $8.7 \text{ km}^3$  of ice loss occurred since the 1920s, and a further  $3.5 \text{ km}^3$  of ice mass were lost between 1980 and the present day.

This study aims to address three aspects of how changing temperatures and reducing ice areas influence meltwater runoff.

1. Modelling runoff response from scenarios of modified air temperatures and ice areas (e.g. a  $+1^\circ\text{C}$  scenario with 20% reduced ice area), with the aim of finding the extent to which the modified conditions influence ice melt. In order to model runoff response, a temperature index model called RRM (Runoff Response Model) was set up. RRM uses formulae to calculate runoff by inputting the following forcing variables to the model: positive air temperature values, and ice area measurements by elevation band, together with a degree day factor (DDF), and an air temperature lapse rate.

2. By using the same method, the effects of climate variations on ice area were investigated by generating modelled runoff quantities from each elevation band. The purpose of doing this was to indicate how various areas of the glacier contribute differing quantities of melt to runoff during the ablation season, and the potential impact of loss of areas of ice. Using the model to show the highest contributing areas was applied to Gornergletscher using the hypsometry of the basin – the second largest glacier in the Alps. Gornergletscher differs from other Alpine glaciers as a result of its wide and relatively flat trunk.

3. The study aims to calculate whether there is a linear or non-linear trend in ice area change with elevation following model tuning. It is generally thought with Gornergletscher that greatest ice areas are distributed at mid-elevations around the trunk, where the tributaries join or joined the main ice body. Ice area in theory should be most liable to melt at low and mid-elevations where both positive degree days and exposed ice areas exceed those of higher elevations. The influence of basin hypsometry on ice area change was studied by modifying the model to respond to differing scenarios of energy availability and ice area available for melt.

The investigation aimed to calculate whether there is a linear/non-linear relationship between ice area change and elevation in a modified climate scenario. It is considered for Gornergletscher, that surface ice area distribution is greatest at mid-elevations, where tributaries connect to the main glacier body. Ice melt in theory should be produced most at mid-elevations where both - more ice area is exposed than that of lower elevations and positive degree days exceed those of higher elevations.

Basin hypsometry is of interest for ice area changes because of the irregular ice area distribution with elevation in the basin. The relationship between the wide and flat hypsometry of the Gornera Basin and ice melt at elevation was considered by modifying the model input values to reflect different scenarios of energy availability and ice area available for melt.

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## 1.0 Introduction

With the expected future decline of alpine glaciers there is growing concern about water supply security in the European Alps (Beniston, 2003; Viviroli et al., 2011) and, more significantly, in other dry mountain ranges such as the South American Andes and central Asian Tien Shan (Kaser et al., 2003; Casassa et al., 2009). Summer runoff from ice-covered basins provides a dependable water source in mountains and surrounding regions, relying on warm summer climatic conditions.

Glaciers are both water stores which contribute a substantial proportion of water to the global hydrological cycle, and also sensitive indicators of climatic change. Climate change and variability will significantly adjust the runoff regime of streams draining from glacierised basins. As a result of glacier thinning, retreat and wastage over the coming decades climatic changes are likely to impact natural and human environments in mountainous regions. Water resources are expected ultimately to diminish in glacier-fed watersheds, after a period of initial increase, and significant societal impacts in mountainous regions are therefore anticipated (Burlando et al., 2002; Ohmura, 2001; Jansson et al., 2003).

Changes in ice area for a glacierised basin are found by calculating:

*Melt per unit area = F (energy availability),*

*Q (discharge) = melt per unit area × ice area.*

This means that as air temperatures warm, melt per unit area will increase. However, as glaciers melt, ice area decreases. Runoff during summer months is controlled by how warm it is and the area of ice available to be melted.

Ice area availability for melt depends on where the ice is in the basin (air temperature is higher at lower elevations); a lapse rate of  $-0.6^{\circ}\text{C}/100\text{m}$  (Quick and Pipes, 1977) is generally assumed. Therefore if a greater ice area is distributed at lower elevations where air temperature is highest, then runoff would be increased.

Glacier size and extent are of specific interest, and monitoring their change is essential for future generations (Oerlemans and Klok 2004). For this reason, it is important to assess the impact of climate change and glacier retreat on high alpine runoff, and to develop methods for its prediction in order to be prepared for the new environmental situation (Huss et al., 2008). Glaciers have a significant influence on downstream river flow, mainly during summer months when they are the primary source of water in Alpine environments. Glacier ice area is a key factor, influencing runoff volume during summer months, and a smaller basin ice area would reduce the portion of ice melt in stream flow and increase snow melt (Horton et al., 2006). Snowmelt dominated summer regimes would considerably lower stream flow, and river flow would increasingly reflect rainfall levels during summer months.

Over many years within a decadal scale, climatic variation naturally happens resulting in dry winters whereby accumulation of snow and ice is reduced, and warm summers where ice melt exceeds the mean value. These dry winters reduce the supply of stored snow and ice to runoff during summers when air temperatures are increased (warm summers). Therefore, declining ice volume in glacierised basins will initially enhance annual runoff totals and remain elevated thereafter over one or two decades, eventually becoming reduced and reflected by declining glacier size.

Peak flow in pro-glacial streams arises typically during early August, although this may alter to early summer after a sustained period (on a decadal time scale) of declining ice volume (Braun et al., 2000). Glacier sensitivity to climatic variation can be gauged by studying the relationship between energy availability (air temperature) and stream flow draining from a glacierised basin. The amount of precipitation during winter months sustained over a decadal scale determines glacier sensitivity, and susceptibility to ice volume change. These changes to runoff regimes in glacierised high mountain basins will create many challenges in mountain regions globally; particularly for water stores in the near future.

The relationships between climate change and stream flow variation have been investigated e.g. in the Swiss Alps (Hock, 1999; Collins 2006; Huss et al., 2008), in the Himalayas (Collins et al., 2013), and in the Andes (Bradley, 2006). Several models currently exist and have been applied to model runoff response from drainage

basins (e.g. Hock 1999, 2003; Schaefli et al., 2007) to investigate runoff response change in relation to climatic parameters. These methods provide sufficiently accurate models of runoff draining from highly glacierised basins (Klok et al., 2001; Huss et al., 2008). Runoff models are usually calculated using at least one existing data set (e.g. air temperature or precipitation) in order to derive results founded on the positive relationship between glacier sensitivity and numerous climatic variables.

Runoff models generally assume glaciers in a crude invariable state, with regards to their spatial and temporal ice geometry (Bergstrom, 1995; Oerlemans, 2011). Other calculations have however considered area and dimension changes to regional climate variability, e.g. (Schaefli et al., 2007; Paul and Haeberli, 2008). The regional climate model (RCM) (Schaefli et al., 2007) modified output by using area calculations and localised climate data from several glaciers to simulate runoff over a 29 year period. The study found; (i) at the temporal horizon considered, global mean warming will have a negative impact on runoff and hydropower production (ii) The regional climate response to a global-mean warming involves prediction uncertainties of the same order as the uncertainty in the global-mean warming itself.

Ice models have also been used to forecast future changes in ice volume; this is typically modelled by combining mass balance measurements and ice dynamics from individual glaciers (Oerlemans et al., 2008; Zhang, 2012). These modified models typically output information on glacier surface and area change over time e.g. (Huss et al., 2008). As aforementioned the complexity of these models may generate more accurate results than a degree day model, although they do require extensive field-measured data and calculation time, thus often over complicating their application to intricate glaciers and their drainage systems.

This study designs a Runoff Response Model, which uses air temperature measurements collected at Gornergrat (3089m.a.s.l), Canton Valais, Switzerland. The model uses existing climate data to generate representative runoff values for the glacier Gornergletscher, and the model is modified for a number of different climate scenarios by altering air temperature e.g. +1°C; +2°C; +3°C. Elevation bands (every 100m.a.s.l) of the study basin are calculated using satellite imagery and GIS

techniques to measure the amount of ice distributed at each elevation. The data entered into the model will use formulae (detailed in chapter 3. Methods) to calculate daily runoff values derived from air temperature measurements and ice area dimensions.

It is thought different glaciers respond uniquely to change in regional climate; though in theory changes in runoff following negative ice area change are expected to yield increased runoff values, and then decline as the air temperature value is tuned to +2°C and +3°C. It is also expected that when winter precipitation is increased in the model then during the following summer runoff will be amplified. Following reduced winter precipitation over a number of years, then it is probable this will contribute negatively to basin ice area.

This study applies a runoff model to a basin containing a wide flat glacier (Gornergletscher); the characteristic ice distribution of this glacier is of specific interest and how its shape and size reacts to variation in climate parameters. Gornergletscher, is one of the widest glaciers in the Alps (Collins, unpublished). In the ablation zone, between 2600 and 2400 m of altitude, the surface is relatively planar with a number of conduit channels visible at the surface; this morphological condition allows the development of the surface drainage of meltwater.

This characteristic is expected to have a negative impact on glacier ice area over a decadal period due to Gornergletschers ice volume distribution at lower elevations. This is because a large portion of the glaciers total ice area is distributed within low-mid elevation bands, therefore air temperature increase is likely to increase ice melt and ultimately decrease ice area. It is of specific interest to investigate how Gornergletscher responds to ice area change and a modified runoff regime by tuning the model to different localised climate signals. A negative change in ice area and increased air temperature would typically see a glacier respond with a ‘smoother’ regime reflected in lower magnitude runoff events; however this is strongly dictated by ice area distribution within the basin.

### 1.0.1 Aims

This research has three main questions that have been considered, which form an investigation of climate change and the runoff response from a glacier which has a wide basin distribution and flat planar;

1. Modelled runoff response from modified air temperature and ice area (e.g. +1°C scenario), with the aim of finding how this influences ice melt. In order to model runoff response a temperature index model called RRM (Runoff Response Model) is formed, and uses formulae to calculate a runoff model by inputting the following; positive air temperature values, a degree day factor (DDF), an air temperature lapse rate and ice area measurements at each elevation band.

As previously stated, by enhancing energy availability, it would be expected that over several decades this would initially yield an increased runoff, but this volume would eventually decline as percentage glacierisation decreases.

2. In using the same method, the affect of climate variation on ice area is investigated by generating values representative of runoff quantity from each elevation band. The purpose of doing this was to indicate areas of the glacier contributing most to runoff during the ablation season, and the potential areas of ice loss. Using the model to show the highest contribution areas was applied to Gornergletscher because of the hypsometrical distribution of the basin – being the second largest glacier in the Alps (Collins, 1999; 2008) Gornergletscher is different from most Alpine glaciers due to its wide flat nature.

3. The study will aim to calculate whether there is a linear or non-linear trend in ice area change with elevation following model tuning. It is generally thought with Gornergletscher that greatest surface ice areas are distributed at mid-elevations around the trunk, where the tributaries join the main body. Ice area in theory should be most liable to melt at low and mid-elevations where positive degree days and exposed ice areas exceed those of higher elevations. It is of interest to examine the influence of



basin hypsometry on ice area change by modifying the model to different scenarios of energy availability and ice area available for melt.

These aims were designed to form an investigation of runoff response, from a basin with an unusual hypsometry containing an alpine glacier, by tuning a model to alternate air temperature and ice area values. The glaciers short term response is indicated by modelling runoff and the affect on ice area. Runoff contribution by elevation band was modelled, and the influence this has on basin hypsometry investigated. Each of these aspects will be represented in sub-sections throughout the study, by analysis of the investigation design to form a final comprehensive and conclusive picture.

### 1.0.2 Study Area

Gornergletscher is a large valley glacier formed by the confluence of two flow tributaries descending from the Monte-Rosa massif located in southern Switzerland. Gornergletscher is approximately 4.5 km long and up to 350 m thick at the centre of flow convergence. Upstream of the confluence, where the two tributaries meet, the ice-marginal lake Gornersee exists. Typically, Gornersee starts to fill by melt water retention during spring and usually drains catastrophically under Gornergletscher once every summer (Collins, 1998).

Field measurements were taken during the period January – December 2008 for the basin containing Gornergletscher (fig.2.1), Pennine Alps, Kanton Wallis, Switzerland. Actual discharge was recorded at the gauging station located on the proglacial meltwater stream drained by Gornera, approximately 1.6 km downstream of the Gornergletscher terminus. Air temperature was recorded at Gornergrat weather station situated 3 km East of Zermatt, located between Gornergletscher and Findelengletscher at an elevation of 3089 m.a.s.l.



**Figure 1.1** Gornergletscher and the highly glacierised catchment area. Google Earth, (accessed on 30/10/2012)

The catchment area of Gornergletscher covers  $82 \text{ km}^2$ , of which 85% is permanently ice covered. Terminus elevation is  $\sim 2005 \text{ m.a.s.l.}$  and the highest point of the catchment is located at  $4634 \text{ m.a.s.l.}$

Gornergletscher is not a typically distributed glacier due to its basin hypsometry, which is wide and flat with large ice areas distributed at mid-elevations. Gornergletscher is different from other glaciers such as Findelengletscher, in that the single pro-glacial stream that runoff drains into, makes its transit through a gorge, therefore the majority of runoff from the glacier can be measured. This direct runoff system is characterised by the tapered terminus of Gornergletscher, which would typically be feature of a narrow glacier and basin such as Findelengletscher.

Usually glaciers with a basin hypsometry similar to Gornergletscher would be drained by several pro-glacial streams, as a result of flat basin topography toward the terminus allowing the formation of several runoff routes during peak flows. Subsequently

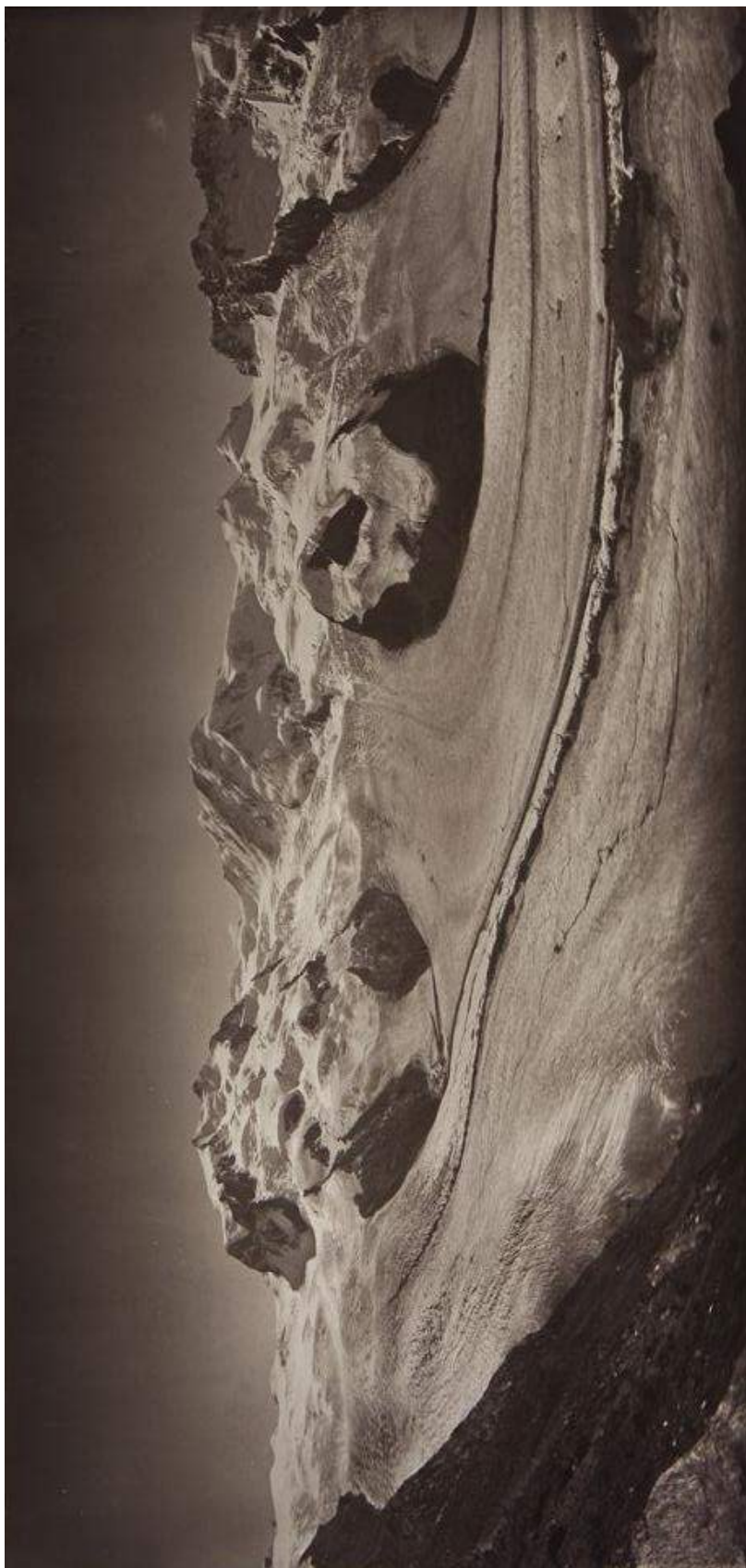
gauging discharge at Gornergletscher is representative of total runoff and more reliable data is produced. Since runoff from Gornergletscher has a direct transit from glacier to gauge, the majority of runoff is measured at a single gauging station, rather than taking several runoff routing drainage pathways.

Historic and contemporary imagery (overleaf) taken from Gornergrat overlooking Gornergletscher shows much greater ice area coverage 150 years ago compared to present day, and it is considered c.1850 was the beginning of gradual climate warming after the Little Ice Age maximum glacier extent (Collins, 2006; Begert et al., 2005), and Swiss Alpine glaciers started to decline (Collins, 2008). The most notable changes in the basin from the historic and contemporary imagery (shown below) are changes to tributary extent, and the main body width of Gornergletscher.



**Figure 1.2** The view from Gornegrat 1879 and 2008. ([flickr.com/photos/thevibrantimage/](https://www.flickr.com/photos/thevibrantimage/); Accessed 12/10/2013).





**Figure 1.3** Monte Rosa, Lys Raum, Castor and Pollux, and Breithorn from Gornegrat, 1850. Albumen Silver Print. (Braun, 1850)



**Figure 1.4** Gornergletscher and tributaries, August 2012. (Google Earth Imagery; Accessed 12/10/2013)

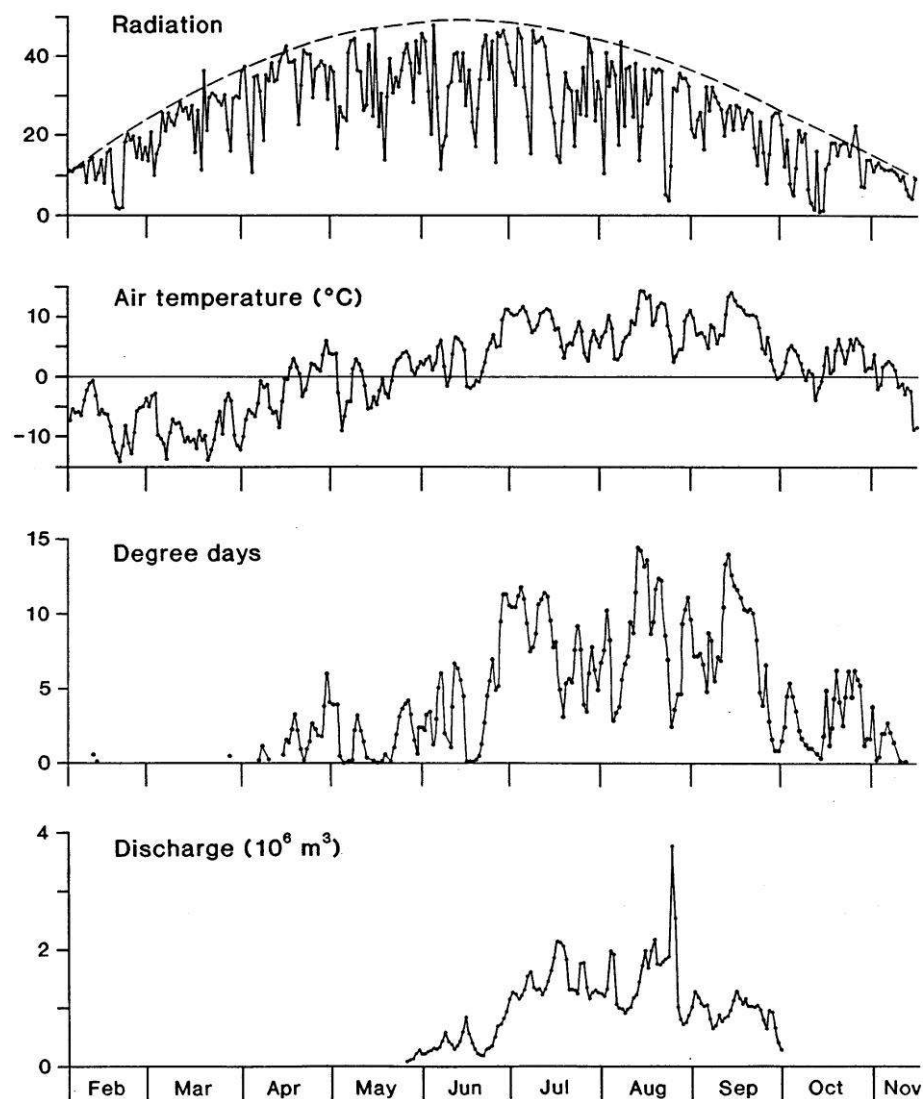
Glacier thinning is the most apparent change over time for Gornergletscher, the once ice-covered portions at low to mid elevations and tributaries have been reduced with declining glacier width. The earlier images of the basin containing Gornergletscher represent a period after the little ice age maximum (1850), when Swiss Alpine glaciers had undergone an extended period of growth. Over the past 150 years the area of ice-free zones in the basin have increased, and are indicated by the extent of tributary retreat to higher elevations, where air temperatures are lower during summer months.

Since the Little Ice Age Maximum extent Gornergletscher has revealed a strong link between climatic variability and ice-coverage indicated by a retreat in length of approximately 2500m between 1882 and 2014. Swiss Alpine glaciers revealed a total ice area loss, of 8.7 km<sup>3</sup> between the 1920s and 1980, and a 3.5 km<sup>3</sup> loss between the 1980s and present day. (Huss et al 2007). These changes in ice area are exemplified in the historic imagery, indicating the affect of changing climate on low-mid elevations of Gornergletscher, and are characterised by deglaciation features such as; tributary separation, pro-glacial lake formation and narrowing of body width. The main body of Gornergletscher is subject to narrowing – a result the glaciers wide flat planar and basin hypsometry, therefore mid-elevation zones are expected to contribute most to runoff during warm summers. It is expected that runoff will be highest from mid-elevation bands; where there is a positive balance between high ice area distribution and a high frequency of positive degree days during summer.

## 2.0 Background

### 2.0.1 Climate change and runoff

Solar radiation is produced at different levels throughout the year, e.g. the summer solstice (June 21) is when radiation peaks and winter solstice (December 21) is when radiation is lowest. Such changes in annual solar radiation directly affect air temperature, in that high levels of radiation result in warm air temperatures (Oerlemans and Klok, 2004). Additionally, during winter months when air temperatures are cold this directly corresponds to lower levels of solar radiation.



**Figure 2.1** The relationship between solar radiation, air temperature, degree days, and discharge for the year 1987 (Collins, Unpublished).

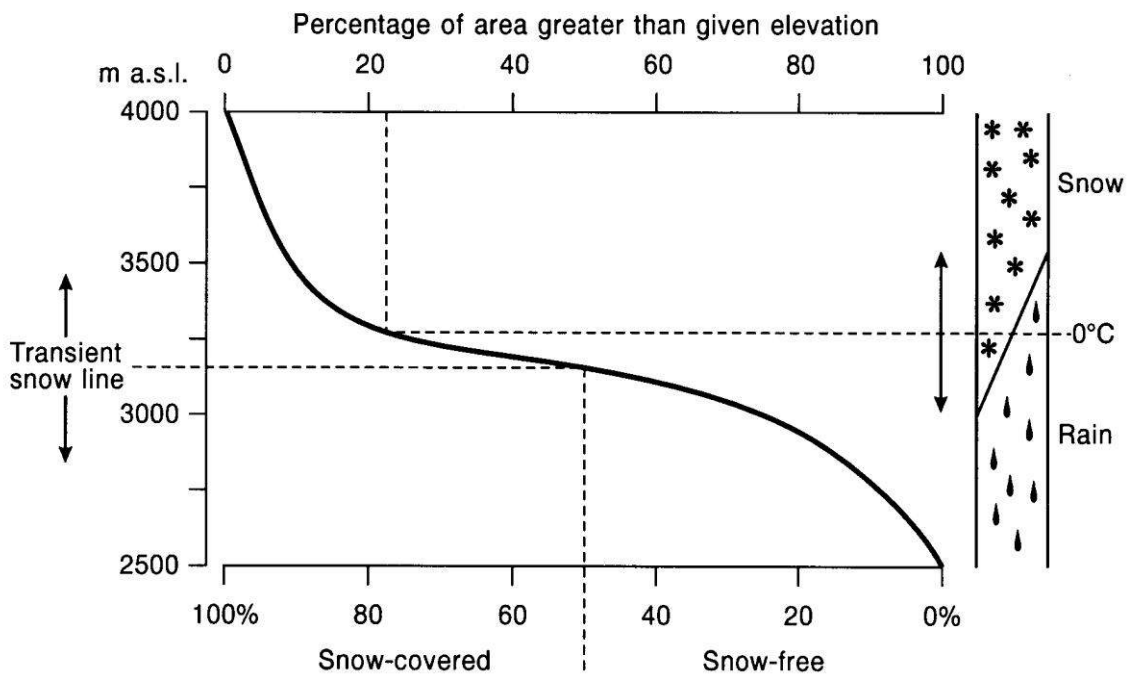


Radiation accounts for 70-80% of the energy supplied for melting snow and ice (e.g. Paterson, 1994). However the total amount of solar radiation for melting is not entirely absorbed by the snow and ice due to their reflectivity properties. The reflective properties of ice and snow coverage are measured with an albedo factor, which is a non-dimensional amount that indicates how well a surface reflects solar energy. Albedo varies between 0 and 1, and is measured by the reflectivity (Escher-Vetter and Siebers, 2007) 'whiteness' of a surface, with 0 equalling high absorption and 1 equalling low absorption of solar radiation. Snow is generally recognised as having an albedo of 0.7 – 0.8 (low absorption) and ice 0.2 – 0.3 (high absorption) (Warren, 1980; Oerlemans and Klok, 2004). Therefore the quantity of ice in a basin during summer strongly influences the runoff regime; as basin surface covering (snow or ice) during high levels of solar energy influences the amount of radiation absorbed.

The quantity of ice exposed as surface covering in a basin in summer is determined by winter snowfall and air temperatures during spring/early summer. During early spring a large proportion of the surface ice areas in a basin are snow covered due to winter snowfall, however this covering begins to reduce as solar radiation levels rise (after March 21). Furthermore, air temperature increases with amplified solar radiation, which gradually melts the winter snowpack; and additional snowpack melting requires greater air temperatures.

It is for this reason that basin hypsometry influences the area of snow and ice available for melt. However, more energy is required to melt surface snow, except air temperature decreases with elevation (lapse rate). The global average lapse rate indicates that air temperature decreases by approximately 0.6°C for every 100m rise in basin elevation (Quick and Pipes, 1972; Barry, 1992), however on a spatial scale this rate is significantly variable. This gradual change in air temperature influences the quantity of surface snow because the transient snowline ascends as far as energy availability dictates. At high elevation where air temperatures become insufficient to melt snow e.g. 3300 - 3700 m a.s.l (metres above sea level) the glacier surface remains snow covered (Lebedeva, 1975). 0°C air temperature isotherm is the name given to the limit/area of snow which is not subject to melting (Collins, 1998) due to the inability to maintain positive temperatures at elevation.

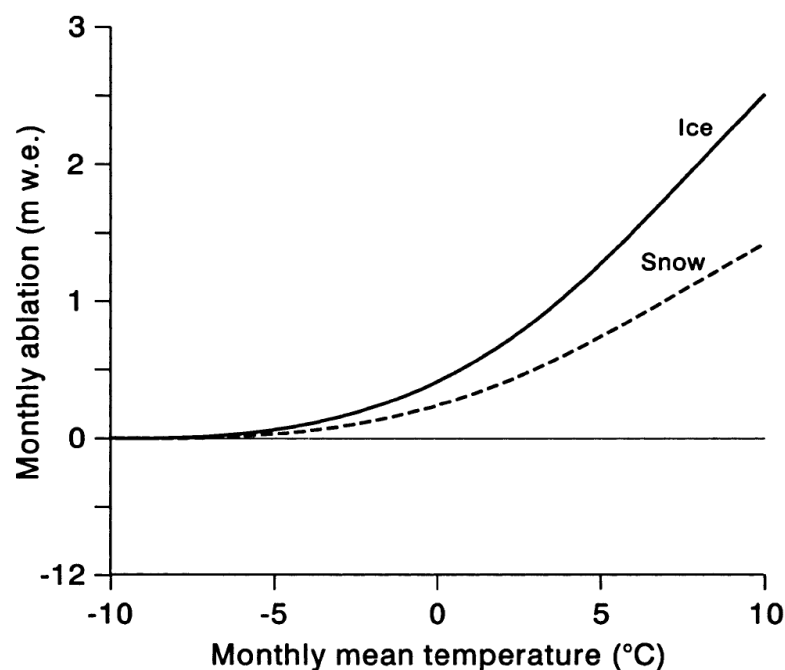
The action of the snowpack ascending to higher elevations is termed ‘the transient snowline’, and refers to the position and coverage of snow across the glacier during summer months. As air temperatures gradually increase during summer the transient snow-line ascends (Jansson et al., 2003) to elevations where energy for melt is much lower. Throughout summer, air temperatures continue to rise after peak radiation, and therefore the transit of the snowline continues to ascend to higher elevations. During summer months, snowline positioning indicates the altitude at which energy availability for melt becomes much lower, e.g. 3300 - 3700m a.s.l. (figure 2.2, below).



**Figure 2.2** Schematic diagram showing how vertical movements of the transient snow-line interact with Alpine basin hypsometry to determine the proportions of the basin area that are snow free and snow covered, and how the 0°C air temperature isotherm similarly interacts to partition the basin area into portions over which precipitation falls as snow and rain (Collins, 1998).

The area of the glacier that is snow-free, as the snowline ascends is for the most part surface ice, which absorbs more long wave radiation for melt than snow does. Therefore, depending on the length of time it takes for the transient snowline to reach its maximum extent should dictate the quantity of summer ice melt to an extent (Fountain and Tangborn, 1985; Chen and Ohmura, 1990). If in early summer the basin snow cover is lower than usual then the snowline could be expected to ascend quickly (Jansson et al., 2003) to higher elevations. As a result of snow being melted off during early summer; a greater ice area will be exposed to higher, air temperatures for a greater length of time during late July and August.

Melting-off of snow cover and glacier ice is known as ablation, which for the most part happens during summer months when there is greater energy availability for melting snow and ice (figure 2.3, below). The runoff from glaciers during the middle to late summer period is directly influenced by radiation, and the amount of melt for runoff during this time mostly depends on the amount of water stored as ice. This ice-melt strongly affects the runoff regime in glacierised mountain basins and is an important source of runoff during summer months (Kuhn and Batlogg, 1998; Jansson et al., 2003). Moreover, the quantity of water supplied by a glacier in summer is a product of the total energy available for melting.



**Figure 2.3** Monthly ablation for snow and ice (m w.e.) meters of water equivalent vs. monthly mean temperatures assuming that temperatures are normally distributed within the month (Braithwaite and Zhang, 2000).

The variability of summer air temperatures over a number of years influences the runoff regime of glacierised basins due to snow and ice stores. Year-to-year climatic fluctuations affect both the amounts of snow and ice stored in, and the amount of meltwater runoff arising from, glacierised high mountain basins. Since much of the streamflow from highly-glacierised areas is derived from melting of ice, annual meltwater yield is directly related to summer energy contribution (Collins 1985), although the precipitation - runoff relationship is more complicated, because summer runoff can be reduced even following a winter of high accumulation. This happens

due to more snow covering the glacier during summer months (Chen and Ohmura, 1990), ascent of the transient snowline is delayed, and this reduces the time and area extent of ice (beneath the snow) exposure to summer energy input.

During these summers of lower ice contribution to runoff some return for the loss of ice melt is provided, however, by the larger contribution of snow melt to runoff (Krimmel & Tangborn, 1974). However due to the density of ice being much greater than that of snow, then streamflow from the glacier is likely to be lower. In an ice-free basin annual total runoff will be directly related to, and always less than, precipitation received. On the other hand, runoff from glacierised basins can be either greater or less than total precipitation according to the change in glacier storage (Collins 1987). Annual runoff during summer months is expected to reflect how water is stored as snow and ice in the basin (Jansson et al., 2003); if snow cover is low then ice melt should be high (increased runoff), whereas if snow cover is high then ice melt would be lowered (decreased runoff), and if both snow and ice area coverage are low then precipitation will contribute to runoff (decreased runoff). This is a result of the expected decrease of snow and ice areas in glacierised basins by amplified air temperatures, resulting in the direct runoff of precipitation (rain) rather than stored snow/ice from winter months being melted during ablation conditions.

### 2.0.2 Temperature Index Modelling

The melting of snow and ice is assumed to be related to air temperature if air temperature is above a critical 0°C threshold (Collins 1987), generally close to the melting point of ice. In particular, the amount of snow or ice melted at a certain place, during a certain period, is assumed proportional to the sum of positive temperatures (on the Celsius scale) at the same location and during the same period (Hock 1999). The quantity of melt is linked to this positive degree-day sum by the degree-day factor. Furthermore, air temperature refers to conventional measurements made 2 m (T2m) above the snow or ice surface (Hock 2003), or measured from a similar station in the same region.

Computation of the melt rate using air temperature is generally a simple function of either the mean temperature for a period of time or positive degree day data. The computation provides the melt rate with an adequate accuracy for most practical uses.

Because it is a relatively simple concept (e.g. Reeh, 1989), it is often regarded as a crude method, and inferior to other more sophisticated methods such as the energy balance method (Ohmura, 2001). The method is used for the reason that temperature data are easily available, and that obtaining energy balance fluxes is difficult.

Whether the mean temperature or PDD (positive degree day) is used for modelling, the melt rate of snow and ice can be calculated with sufficient accuracy for practical applications. This type of estimation relies on a suitably chosen melt-to-temperature sensitivity factor ( $\text{mm w.e. } ^\circ\text{C}^{-1}$ , where w.e. is water equivalent) or the PDD factor ( $\text{mm w.e. } ^\circ\text{C}^{-1}$ ) - all approximate energy balance information is included in these factors (Ohmura, 2001). The variability of the PDD factor over time and space has previously been analysed qualitatively (e.g. Lang and Braun, 1990) and quantitatively (e.g. Braithwaite, 1995). The modelling accuracy by these and other field experiments (e.g., Lang 1986) is sufficiently high for most practical applications. There are however, further studies and investigations which aim to improve the temperature-index modelling method by defining model parameters at a greater level of accuracy e.g. the use of ice area data (imagery) during a period of time rather than deriving from one image. This degree of data availability would improve the temporal resolution of the model by simulating runoff from the glacier during different periods of the summer when ice area is continually changing.

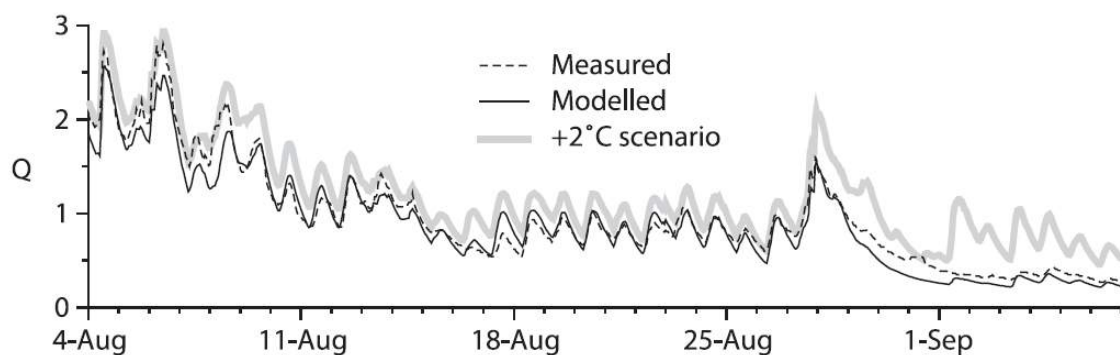
Temperature index or degree-day models depend on the positive relationship between snow or ice melt and air temperature, which are typically expressed in the form of positive temperatures (Hock 2003). These models apply air temperature as the primary data set, using a degree day factor, which is an approximate figure derived from a range of glacier-specific parameters. Ice area data is also used in runoff modelling which will generate the quantity of ice melt from corresponding air temperatures in the model.

A degree day is where air temperature values maintain a single temperature e.g.  $3^\circ\text{C}$  through 24 hours with little or no variation, without dropping below the  $0^\circ\text{C}$  threshold (Braithwaite, 1995; Hock 1999). Ice and snow melt runoff can be modelled by using positive temperatures, and ultimately variance in air temperature is reflected in runoff

from the basin. The model is founded on glacier sensitivity to changes in climate; in mountainous regions, snow and ice considerably affect catchment hydrology (Jansson et al 2003) by temporarily storing and releasing water on various time scales.

Temperature-index models assume a relationship between air temperatures and melt rates. This relationship was first investigated for an Alpine glacier by Finsterwalder and Schunk (1887) and has been widely used and refined over recent decades (e.g. Clyde, 1931; Collins, 1934; Quick and Pipes, 1977; Braithwaite, 1995; Hock 1999). Temperature-index methods are widely used in melt modelling and are regarded (e.g. Ohmura, 2001; Braithwaite, 1995; Hock, 2003) as a reliable method to calculate melt runoff. Temperature-index models have been the most frequently used approach when simulating melt for the following reasons; readily available and extensive air temperature records; the forecasting potential of future runoff response; and uncomplicated computation methods.

An example of temperature-index modelling is provided (Fig. 2.4); the model runs over a 5 week period for Storglaciären, a glacier in Sweden. Modelled runoff, measured runoff, and a tuned air temperature scenario (+2°C) are shown in the graph. Modelled runoff deviates slightly from measured runoff, and the tuned air temperature (+2°C) scenario indicates an increased level of runoff from the other series in the graph.



**Figure 2.4** Example of modelled runoff from a glacierised basin - Measured and simulated daily discharge (Q) from Storglaciären, Sweden, 4 August to 6 September 1994. The model is also tuned to an increased air temperature scenario (+2°C) to show the response of runoff (grey line) (Hock and Jansson, 2005).

The Storglaciären model (Hock and Jansson, 2005) provides a similar approach to the Gornergletscher runoff model, because air temperature data is modified to different scenarios in order to simulate ice melt response to higher temperatures. Hock and Jansson (2005) modify their simulation by increasing air temperatures in the model, which after calculation reported a positive correlation with measured runoff. However, simulated runoff is shown to not follow the same pattern as monitored runoff during periods of decreased flows.

A critical part of the temperature index model is to ensure a degree day factor (DDF) is used that is representative of the study glacier. The DDF takes in to account external parameters which would influence the energy available for melt (e.g. Braithwaite, 1995; Braithwaite and Zhang, 2000; Hock, 2003, 2005), and therefore DDF is changeable for different regions e.g. DDFs differ in maritime regions from continental regions.

The DDF is only a function used in the computation that links the amount of melt to the positive degree day sum, and is critical to accurately model summer runoff response. Different factors are used in calculating snow melt and ice melt, due to their varying sensitivities to changes in climate parameters e.g. albedo. The generally lower degree-day factor for melting snow compared with ice is mainly due to higher albedo which reduces the energy available for melting (Braithwaite, 1995), while time variations at the same locations most probably reflect differing weather conditions. However, Huss and Bauder (2009) identify year-to-year variations in glacier averaged degree day factors for Swiss glaciers (roughly equal to the degree-day factor for snow) which they claim is a result of global radiation variability. This regional difference in DDF indicates the high sensitivity of Swiss glaciers to melting parameters compared to e.g. Himalayan Glaciers.

### 2.0.3 Uses of Temperature Index Modelling

Typically, a temperature-index model excludes snow melt and calculates only ice melt in-line with the degree-day method, e.g. when modelling summer runoff from a glacierised basin, it is common to compute values only for ice without hindering model accuracy. The quantity of snow melt contribution to runoff during mid-summer

is negligible to total runoff; hence summer runoff studies primarily use ice area data to retain the models simplistic approach (e.g. Braun et al., 1995; Hock, 1999).

Simple degree day formulations are a common tool to assess the sensitivity of glacier mass balances to climate change (e.g. Laumann and Reeh, 1993; Braithwaite and Zhang, 1999; Braithwaite and Zhang, 2000). Temperature-index methods can be used to derive a number of models that are representative of glacier response to climate change. Many studies use the degree day method to simulate summer runoff from different glaciers by entering variable data to model a glaciers response (e.g. Braithwaite, 1985; Hock, 1999, 2005; Klok et al., 2001; Verbunt et al., 2003). In connection with runoff models, temperature-index melt models generally provide accurate results on a daily basis (Rango and Martinec, 1995; Hock, 2003), this is because daily variations are smoothed by the basin response.

Another common approach in utilising the temperature index method is to model changes of glacier mass balance. This has previously been undertaken using different variations of the degree day model to compute mass-balances of glaciers in Scandinavia (e.g. Laumann and Reeh, 1993; Braithwaite and Zhang, 2000; Braithwaite et al., 2002; Anderson et al., 2006). The relevant degree-day factors are either found by tuning models onto field data or by trial and error based on previous studies. Typically, modelled accumulation depends upon the degree day factor for snow (e.g. Braithwaite and Raper, 2007), and mass-balance sensitivity depends upon the degree-factor for ice.

Another frequently used application for the degree day method is modelling ice area change in basins containing glaciers. This type of modelling is commonly referred to as ‘distributed snow/ice melt modelling’, and relates to the use of the air temperature lapse rate across the basin, and the area of ice exposed to different levels of warming (e.g. Braun et al., 1995; Hock, 1999). Model verification for these methods can be performed using satellite imagery data, and using comparisons between modelled and measured runoff.



#### 2.0.4 Temperature Index Studies

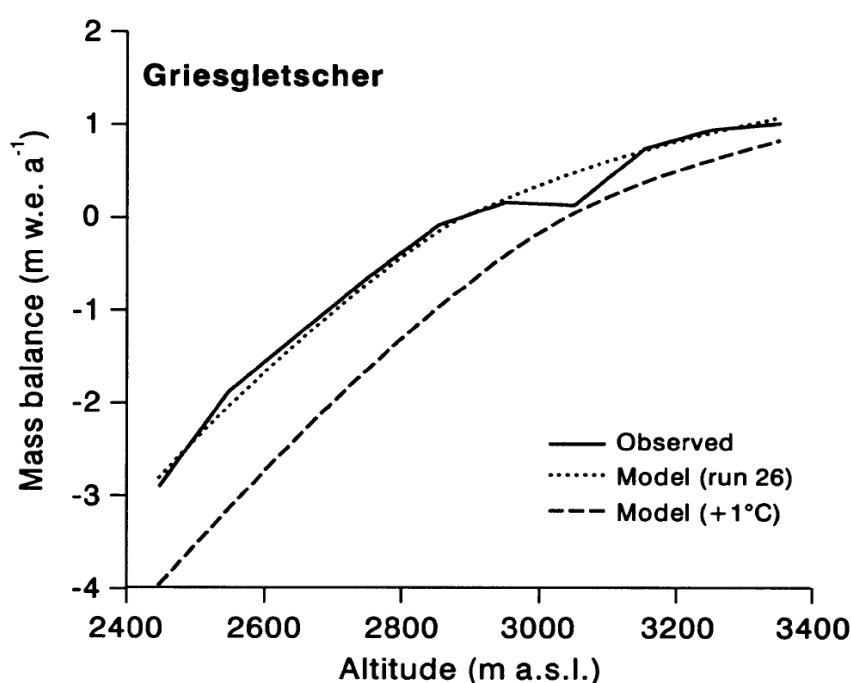
There is generally a relation between the melting of snow and ice with air temperature which can be modelled using the degree day method. The comparative qualities of degree-day and energy-balance methods will continue to be examined, however it is considered both will continually be used for their advantages, for their respective simplistic and comprehensive approach (Braithwaite, 2008). Many investigations use a simpler approach than the degree day model; assuming glacier-melt to be a function of mean summer temperature (e.g. Krenke and Khodakov, 1966). However, a suitably chosen averaging period is critical for this approach, e.g. June-August, May-September or May-October; the summer mean temperature mainly representing the effects of above-freezing temperatures.

The reported success of the degree-day approach to ice and snow melt at two sites in Greenland (Braithwaite and Olesen, 1989) inspired Reeh (1991) to further develop the model and test it with the limited amount of data from other sites in Greenland. Huybrechts et al. (1991) then used the degree day model to calculate changes in mass balance for their model of ice dynamics for the entire Greenland ice sheet, whilst assuming degree day factors of 3 and 8 mm d<sup>-1</sup> K<sup>-1</sup> for snow and ice respectively.

Previous studies have investigated individual aspects of melt modelling, such as; Lang (1986) and Röthlisberger and Lang (1987) discuss modelled glacier melt and discharge processes. Male (1980) examines the processes involved in snow melt and the hydrological regime, while Kirnbauer et al. (1994) focus on distributed snow models, and Male and Granger (1981) explored the effect of radiation and heat exchanges on melt at the glacier surface. Furthermore, the recent developments in temperature index melt modelling are discussed in Hock (2003; 2005). Many of the abovementioned studies have discussed in depth, and assessed the methods used for obtaining representative results that are viable when calibrated.

While previous research has focused on the impact of climate change on glacier mass balance (e.g. Braithwaite and Zhang 2000) and glacier size variations (e.g. Oerlemans, 1994), a limited amount of attention has been paid to the effects on glacier discharge. To assess glacier sensitivity to climate change, models are often affected by minimal

linear shifts in climate data records (e.g. Kuhn and Batlogg 1998; Braithwaite and Zhang 2000). These studies are useful to investigate sensitivities, but hinder the prediction of actual responses to climate change for specific glaciers, as future climate changes will not be homogeneous. The following plot illustrates mass balance results calculated and modelled by Braithwaite and Zhang (2000) for Griesgletscher, Switzerland; and also shows the response of mass balance following a modelled +1°C air temperature scenario.



**Figure 2.5** Modelled mass balance for Griesgletscher for present climate and for a +1°C temperature rise (Braithwaite and Zhang, 1999).

Many studies suggest the accuracy of runoff or ice melt models becomes hindered by their simplicity. Although others imply model simplicity is the separating factor between using temperature-index and energy balance methods. There are numerous parameters both climatologically and glacial that could be accounted for example Hock (2005) highlights that currently, many conceptual runoff models do not include clear routing routines for water transport through the glacier, taking into account the different hydraulic properties of snow, and ice with respect to through flow velocities. Such routines are necessary to accurately capture the effects of amplified diurnal melt, resulting from accelerated runoff generation in response to reduced snow cover ascent under a warming climate.

Taking account of factors such as glacier storage, routing and sub-glacial drainage improves the accuracy of a model and would reduce runoff going unaccounted for. However, some methods are approached in certain studies with a greater simplicity, whereby the data resolution and computation is relatively coarse (e.g. Lang 1986; Braithwaite and Olesen, 1989; Reeh 1991). These studies simply use the connection between air temperature and ice melt to determine a set of runoff values, which are useful for a number of reasons e.g. ice melt volume estimation from certain air temperatures; extrapolation of future runoff patterns; the influence of snow line positioning on the relationship between air temperature and runoff.

Previous studies often use modelling methods from other investigations and modify the input criteria in order to obtain the desired results. Johannesson and Laumann, (1993) compute the MBT (mass balance of temperate glaciers), simulation, and is based on existing hydrological and mass balance degree-day models; the HBV model (Bergstrom, 1976, Bergstrom, 1992), the NAM2 model (Gottlieb, 1980) and the MB1 model (Braithwaite, 1984). The Nordic glacier mass balance model is applied as a general Fortran subroutine MBT and is run from a core program, e.g. a dynamic glacier model. The model determines the melting of snow and ice at each elevation, the ablation, mass balance and runoff is then computed and found that a warming of 2°C is predicted to lead to a 220m or 180m rise in the equilibrium line altitude of Satujokull, for no precipitation or 10% precipitation increase respectively.

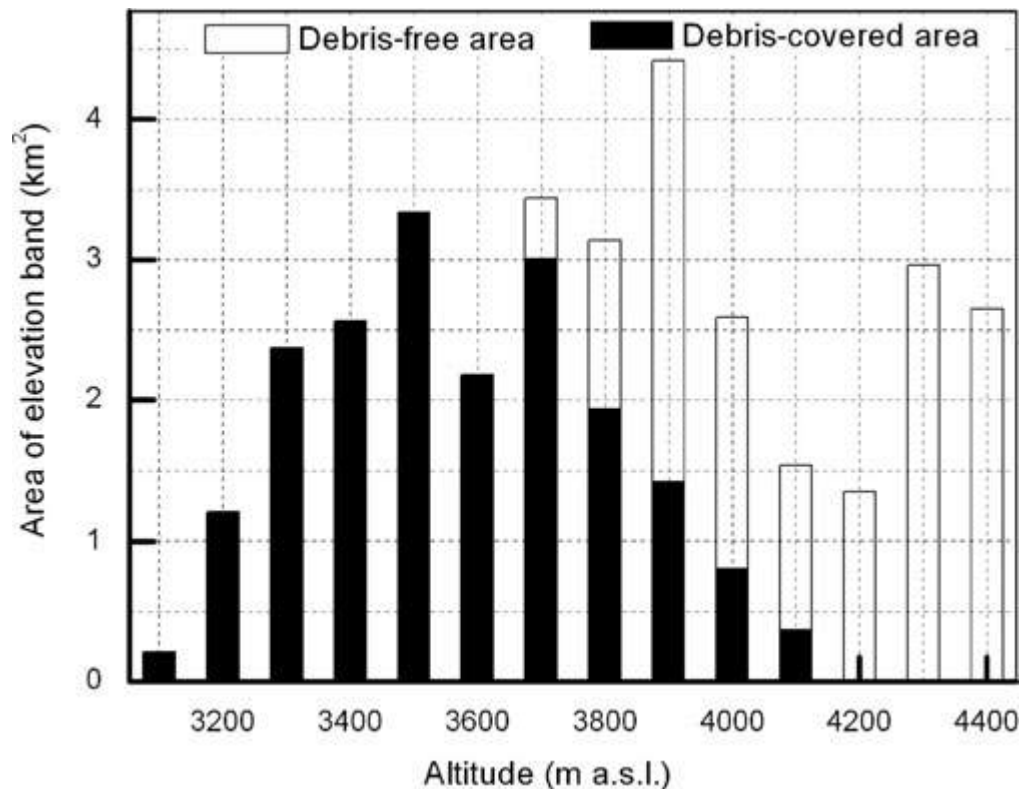
The main program TMBT computed glacier mass balance and included elevation values, and runoff distribution of a mass balance year for the Greenland Ice sheet, which were computed by repeatedly running the model with a required time increment (Reeh, 1991). The Nordic mass balance model modified from the previously active model determines precipitation, snow accumulation, snow/ice melt and refreezing at each elevation. As a result, ablation, mass balance and runoff can be computed.

Modelling glacier response to runoff in highly glacierised, remote areas (e.g. The Himalayas) is a common application for the temperature index model and other mass

balance models (e.g. Zhang et al., 2007). They aim to provide a method for predicting glacier meltwater and runoff in glacierised areas, especially in remote high mountain regions which are not continuously monitored. Zhang et al., (2007) studied Keqicar Baqi glacier, a large glacier in the south western Tien Shan, north west China. They, began by calculating glacier meltwater quantities at each elevation band on the glacier by applying a modified degree-day model (e.g. Hock, 1999), and additionally considering potential clear-sky direct solar radiation. Their calculated meltwater and precipitation are then routed through the glacier via three parallel linear reservoirs. The model was then applied to evaluate the effect of a debris layer on the glacier meltwater and runoff (Figure 2.6 overleaf), and to simulate the response of glacier runoff to different climate-change scenarios (Chen et al., 2006). The study formed the foundation for other ongoing studies of the Keqicar Baqi glaciers mass balance and geometrical changes, and the resulting impact on variations in water resources in the arid regions of North West China.

Applying basin hypsometry to a temperature index model is considered to increase model accuracy (e.g Zhang et al., 2007) by providing a representation of potential runoff volumes from each elevation band. Furthermore, hypsometry is different for every basin, through their unique spatial distribution of ice area. However, glacierised basins share similarities in that they are generally highly elevated and contain areas of ice covered and ice free portions. The ratio between debris-free (ice covered) and debris-covered (ice-free) areas determines runoff distribution by elevation (Braithwaite, 1995; Hock 1999). Basin area typically increases with elevation, and ice area would also be expected to increase with elevation; therefore the warmest elevation bands lack sufficient ice area to melt, whereas at higher altitudes there is insufficient heat energy to melt greater ice areas.

Transient snowline positioning plays a critical role in ice covered portions of a basin during summer months, and should therefore be accounted for in a distributed runoff model. The mean elevation maximum for a transient snowline can be taken for a period of previous years, and will assist in calculating ice area exposure for the given study season.



**Figure 2.6** Hypsometric diagram of Keqicar Baqi glacier for debris-covered and debris-free surface conditions (Zhang et al., 2007).

Once the transient snowline ascends to its maximum summer position then the subsequent weeks are a period when ice area loss is most rapid, and a critical point is reached when glacier runoff is highest. Past this critical point, glacier area reduction would prevail over glacier thinning so that glacier melt is unable to sustain runoff, and finally decreases glacier run-off, with ultimately the glaciers negative mass becoming continuous year-to year.

This effect has been modelled for glaciers in Iceland, and by Pouyaud et al., (2005) and Juen et al., (2007) for glaciers in Cordillera Blanca, Peru. For Iceland, the critical point is reached in 2075 - 2110. In Peru, according to Pouyaud et al., (2005) the critical point occurs in 2025 – 2050, with complete disappearance of glaciers by 2175 – 2250 (Casassa et al., 2009). Initial stages of warming will also result in enhanced diurnal run-off peaks, this is due to melt (Hock, 1999; 2003), followed in a second stage by a decrease of diurnal amplitudes as glaciers decline beyond their critical point.

### **3. Methods**

This section presents an experimental design, and the rationale as to why specific procedures were chosen. The experimental design is explained, and this section describes the processes of how data were collected, analysis undertaken, and the software and model calibration used. The following five key points are incorporated in this section;

1. Description of the materials used in the study.
2. Description of the research protocol.
3. Ice area by elevation calculation: Intersection.
4. Explanation of how measurements were made and calculations performed.
5. Report of the statistical tests undertaken to analyse the data.

This section firstly provides a brief overview as to the data sets used and equipment/software encountered during the investigation. Two sections are provided providing the model design details, and comprise of data collection, treatment and calculation phases. Firstly, the model design phase clarifies the data used and processes undertaken in ArcMap in order to extract satellite imagery data. The second phase explains the treatment of data sets, their computation and the formulae used to produce the model.

Air temperature was recorded at hourly intervals for the entire year of 2008, and discharge measurements were also taken at hourly intervals, for the duration of May through October (table 3.1). Air temperature was recorded at a fixed weather station at Gornergrat, and discharge measurements were taken at Gornera gauging station using a Hach Minisonde - a water quality multi-probe.

**Table 3.1** Specifications of data used to model runoff from Gornergletscher.

<b>Parameter</b>	<b>Location</b>	<b>Period</b>	<b>Elevation</b>
Air Temperature (°C)	Gornergrat weather station (lat. 45.983607°, lon. 7.783609°)	01.01.2008 - 31.12.2008.	3089 m a.s.l
Discharge (m <sup>3</sup> s <sup>-1</sup> )	Gornera Gauging station (lat. 45.989954°, lon. 7.730261°)	07.05.2008 - 30.10.2008.	2006 m a.s.l
Ice Area (km <sup>2</sup> )	Basin containing Gornergletscher	05.08.2009	2200 – 4500 m a.s.l

Discharge was obtained for the 2008 ablation season from the Grand Dixence SA Dam (2006 m a.s.l), the leading supplier of hydro-electrical power in Switzerland, capturing water from 35 glaciers in the Valais, Zermatt region. Air temperature data is readily obtained through MeteoSwiss for Gornergrat weather station (3089 m a.s.l) along with other archive data. MeteoSwiss is the national weather service of Switzerland and provides meteorological and climatological data.

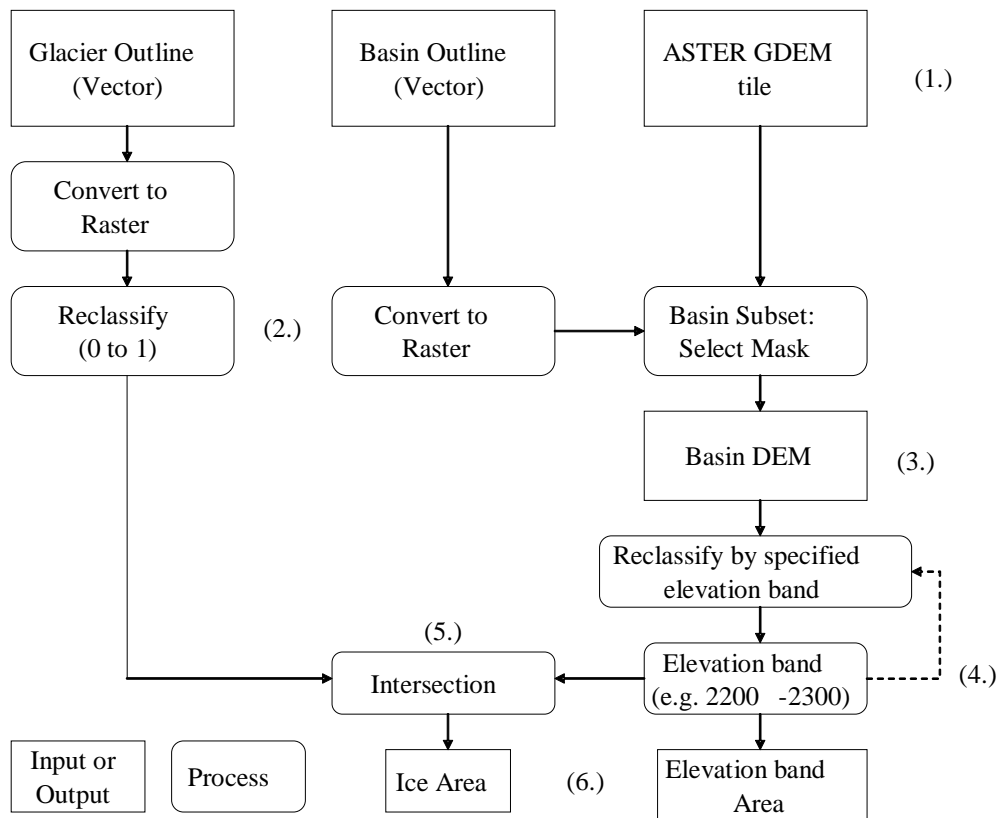
The experimental design for this investigation was designed to form a study of climatic change and the impact on an unusually distributed glacier. Firstly runoff response from air temperature tuning was modelled, with the aim of finding how energy availability influences basin ice area. The hypothesis is that with the manipulation of certain variables, a temperature index model can be formulated to simulate ice melt from a direct variable (air temperature) based on the strong relationship between air temperature and runoff. The experiment of simulating ice melt from air temperature will be tested against actual discharge. In terms of accuracy the simulation cannot be compared to energy balance models as a number of variables such as radiation, precipitation and mass balance measurements are unaccounted for.

The models experimental design is uncomplicated and can be altered in order to manipulate different climate scenario outcomes. Air temperature, ice area and degree day factors can all be changed to influence the out turn and perform different

scenarios e.g. simulated runoff is likely to increase if air temperature input is raised across all elevations by 1°C. Alternatively, ice area at all elevation bands can be changed, and computed to provide a runoff response indicative of basin hypsometry and ice coverage.

### 3.0.1 Calculating glaciated and non-glaciated area by elevation: Intersection

The process to calculate glaciated and non-glaciated area by elevation for the basin containing Gornergletscher was separated into six key stages (fig.3.1); each stage is described in the following sub-sections. The input data for the study area consisted of glacier and basin outlines, and a corresponding ASTER GDEM (version 2) tile. All stages are performed in the GIS software package ArcGIS.



**Figure 3.1** Schematic workflow for calculating glaciated and non-glaciated area by elevation in a specified basin.



### 3.0.2 Data Input

The first step involves assembling the relevant input data. Critical to the overall process of area calculation by elevation is utilisation of an appropriate DEM. In this case the ASTER GDEM (version 2) product was chosen as it offers relatively high resolution elevation information (30 m) that has already been pre-screened for major errors. Corresponding tiles were selected and downloaded via FTP from NASAs REVERB web-interface. In order for the DEM product to integrate efficiently with other spatial datasets, it is recommended they all share a common projected co-ordinate system. Hence, each ASTER GDEM tile is re-projected from GSC WGS 1984 to WGS 1984 UTM. This task was performed using the raster re-project tool within ArcMap.

In order to focus principally on elevation information within a specific basin, a subset of data must be extracted from the DEM. For this reason a basin outline was first delineated from the relevant DEM. The basin delineation process was the same as that followed for glacier delineation in that a vector shapefile was created (in ArcCatalog) and populated by individual point locations manually selected by the user to make a polygon around a given basin (using the Editor tool within ArcMap).

When viewed in a GIS-interface (such as ArcMap) ASTER GDEM tiles are represented by a matrix of brightness values, which correspond to the elevation value of each pixel and the overall elevation range of the tile. These brightness values originally make it difficult to accurately delineate basin boundaries and subsequently a Hillshade raster must be created using the Spatial Analyst tool within ArcMap. The Hillshade tool creates a shaded relief effect on the surface of the DEM. For ice area to be computed by elevation for a given basin, pre-delineated glacier outlines must also be utilised. Glacier outlines are initially input into this process as vectorised shapefile polygon features.

### 3.0.3 Vector conversion and reclassification

Before both the vectorised Glacier and Basin outlines can be used within the next step they must first be converted into a raster format. As mentioned earlier, both datasets consist of individual point locations connected together in the form of a polygon. In

order to operate these datasets within ArcMap Raster Calculator (used later during the basin extraction and intersection process) each polygon feature is separated into pixels.

Raster pixel values can then be integrated into any algebra expression executed with the raster calculator. The conversion process is performed using ArcMap Spatial Analyst feature to raster tool. A vital consideration during the conversion process is pixel size. In this case, both glacier and basin raster datasets were assigned a pixel size of 27.08 x 27.08m which is the same as ASTER GDEM. This aided the pixel intersection stage.

Once transformed to raster datasets, the glacier outlines require an additional reclassification step. Individual pixels of newly converted raster datasets are initially given the value 0. This only acts as a mask during the basin extraction process. Nevertheless, for the raster glacier outlines to be later intersected with individual elevation bands, glacier pixels must be given the value of 1. This pixel reclassification is performed manually using ArcMaps Spatial Analyst reclassify tool.

#### 3.0.4 Basin Subset

Once the basin outline has been converted into a raster format it can be used as a mask to create a subset basin DEM from the original ASTER GDEM tile. This subset DEM simply maintains the elevation information corresponding to the basin of interest. The ‘select by mask’ function (Eq. (1)) is used within ArcMap’s Raster Calculator to create the DEM subset, where InRas1 is the ASTER GDEM tile, InRas2 is the rastered basin outline and OutRas is the subsequent basin subset;

$$\text{OutRas} = \text{SelectMask}(\text{InRas1}, \text{InRas2})$$

#### 3.0.5 Elevation band classification

Now that a subset DEM is produced, individual pixels within this subset can begin to be separated by elevation through use of binary reclassification. In this case 100m elevation bands were utilised. In order to undertake this, all pixels can be separated (each with a specific elevation value) within a specified elevation range (e.g. 2200-2300) need to be assigned a value of 1 with all others given a value of 0.

This involved manually defining elevation zones using ArcMaps Spatial analyst Reclassify tool. The manual input of elevation zones allows pixels to be separated into groups and then designated a different pixel value. In this case 3 classes were generally used. For example if the 2200 – 2300 m.a.s.l elevation band was to be separated, the first class would be assigned at 2200, the second at 2300 and the third would be the maximum elevation for the basin which for Gornergletscher is 4500 (m.a.s.l). These three classes would distribute pixel values into 3 groups; 2100 - 2200 (2100 is the minimum Gornergletscher elevation), 2200 - 2300 and 2300 - 4500. Once distributed in this way, a value of 0 can be assigned to all pixels in the 2100 - 2200 and 2300 -4500 groups and a value of 1 to all pixels in the 2200-2300 group. The consequent raster dataset then effectively highlights all pixels within the 2200 - 2300 series and allows pixel number in respective elevation bands to be quantified. Reclassification by elevation must be repeated for each 100m elevation zone within a basin.

### 3.0.6 Intersection

Now each elevation band is separated and reclassified, they are individually combined with each of the reclassified glacier outlines, and the number of glacier pixels that intersect with specific elevation bands are quantified. To perform this intersection a straightforward expression is implemented with ArcMaps Raster Calculator, whereby an individual raster elevation band is multiplied with the reclassified glacier outline, generating a new intersection raster. Through performing this basic expression, pixels in both datasets that share the same spatial location are multiplied together. Significantly, as both the glacier and elevation band pixels have been assigned the value of 1, thus the intersection raster only highlights glacier pixels that are located within that specific elevation band (because  $1 \times 1 = 1$  and  $0 \times 1 = 0$ ). This intersection process is repeated for each elevation zone that contains ice area.

### 3.0.7 Calculation of glaciated and non glaciated area

Once an intersection raster is formed for every elevation band that contains glacier ice, glaciated and non-glaciated area, all zones can be calculated with relation to the number of pixels. Within each intersection raster ice pixels are assigned a value of 1. Total ice pixels within a specified elevation band can be found by opening the Table

of Contents of the subsequent intersection raster within ArcMap. The areal coverage of pixels can be quantified by first calculating the area of individual pixels, then multiplying this by total ice pixels in an elevation band. The product can then be divided by 1,000,000 to convert to km<sup>2</sup>. These computations were carried out within Microsoft Excel. For calculation of non-glaciated area, ice pixel quantity in an individual elevation band is simply subtracted from the total number pixels in that band.

### 3.0.8 Formulae and model calculation

To create the temperature index model, several steps had to be taken prior to calculation and synthesis of statistics; these included collection, sorting and treatment of the data. Recorded air temperature figures had to be refined and concentrated into a more manageable input format. An entire year of hourly recorded air temperature data is not needed for this model, therefore the set is reduced to just May through September. The following stages outline each calculation and statistical control undertaken to form the runoff response model;

**Table 3.2** The stages of model calculation including formulae and computation methods

<b>Stage</b>	<b>Action</b>
<b>1</b>	All negative air temperature values are removed by using the following formula; IF(A1>=0,A1,""). Only positive air temperature values now remain.
<b>2</b>	Positive degree day hourly air temperature May through September 2008 are summed for every 24 hours, to give daily air temperature totals, and then each day is divided by 24 to produce a diurnal mean air temperature.
<b>3</b>	The air temperature lapse rate is introduced to the original data, it is estimated there is a -0.6°C (Barry, 1992) reduction in air temperature for every 100m increase in elevation.
<b>4</b>	Elevation bands range from 2200 – 4500m a.s.l., so columns are divided in to respective elevation zones and new values are

	obtained by using the lapse rate from original air temperature data. The new values are derived from the original data set collected at 3100m.a.s.l by summing or subtracting 0.6°C. If for example mean daily measured air temperature at 3100m is 5°C then at 3200m it would be 4.4°C, and at 3000m 5.6°C.
<b>5</b>	There are now columns containing each elevation band from 2200 – 4500m a.s.l with daily mean temperatures from positive degree days.
<b>6</b>	A new column is then created next to each elevation band in order to calculate the degree day formula and derive a new data set.
<b>7</b>	The degree day factor for Ice of Gornergletscher is calculated by method of delineation. Previous studies of the DDF of ice in Switzerland do not exist (Hock, 2003), and previous studies only represent snow values, therefore alternate values are tested in order to find the best fit.
<b>8</b>	The elevation band 2200 begins in cell A1, with a new blank column beside where the new calculation will be input derived from column A. The formula in column B is calculated; $=A1*(6*0.21)$ .
<b>9</b>	A1 is the cell containing a positive air temperature value, 6 is the degree day factor for Gornergletscher, and 0.21 is the ice area (km <sup>2</sup> ) at that elevation band.
<b>10</b>	This is then replicated for every day during the ablation season for each respective elevation band. The newly derived columns are subsequently copied in to a new sheet.
<b>11</b>	The new data set reads; day 127 through day 280 in column A of the new sheet with elevation bands across the top (2200 - 4500).

<b>12</b>	There is now a value in every row (day) for each elevation band, even if only a zero as there is no original positive air temperature at the given elevation band for that day.
<b>13</b>	The value for each elevation band in every day is summed to produce a total cumulative simulated runoff per elevation zone.
<b>14</b>	This value then requires to be divided by 100 in order to generate the value into valid total runoff units.
<b>15</b>	Once collective simulated discharge for elevation zones have been calculated, the next stage is to compute diurnal runoff.
<b>16</b>	Each value per day is summed across all elevation bands, resulting in a daily total discharge. This is replicated for every day during the ablation season.
<b>17</b>	These newly derived data need to be divided by 100 to produce a mean diurnal simulated runoff value. This product is average modelled discharge for ablation season 2008, and is set to be plotted beside actual mean runoff from Gornergletscher.

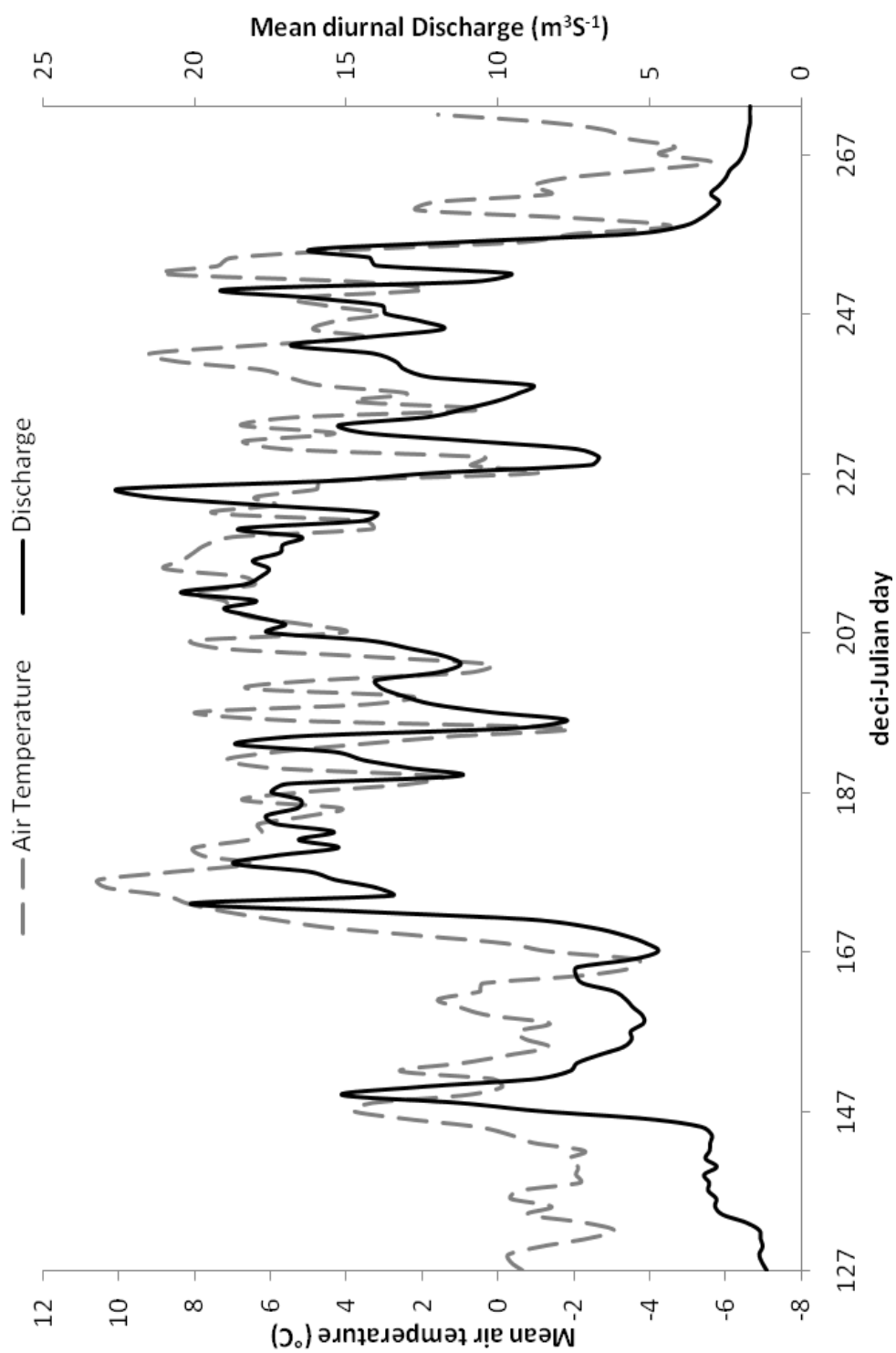
#### **4. Results**

Recorded air temperature data for the summer (May-September) 2008 have been computed to form a model, simulating daily, seasonal, and distributed (100m increments) ice melt runoff for the basin containing Gornergletscher (2200 - 4500 m a.s.l). The model also simulates total melt for ice covered portions of the basin for the scenario of a +1°C, +2°C, and +3°C rise in air temperature, and total modelled ice melt runoff from individual elevation zones.

Firstly plots of measured discharge, measured air temperature and ice area during the ablation season of 2008 were produced. The relationships between input parameters were then identified from the graphs showing the variables controlling ice melt. Next, the modelled runoff data were plotted and described, and then calibrated against actual discharge.

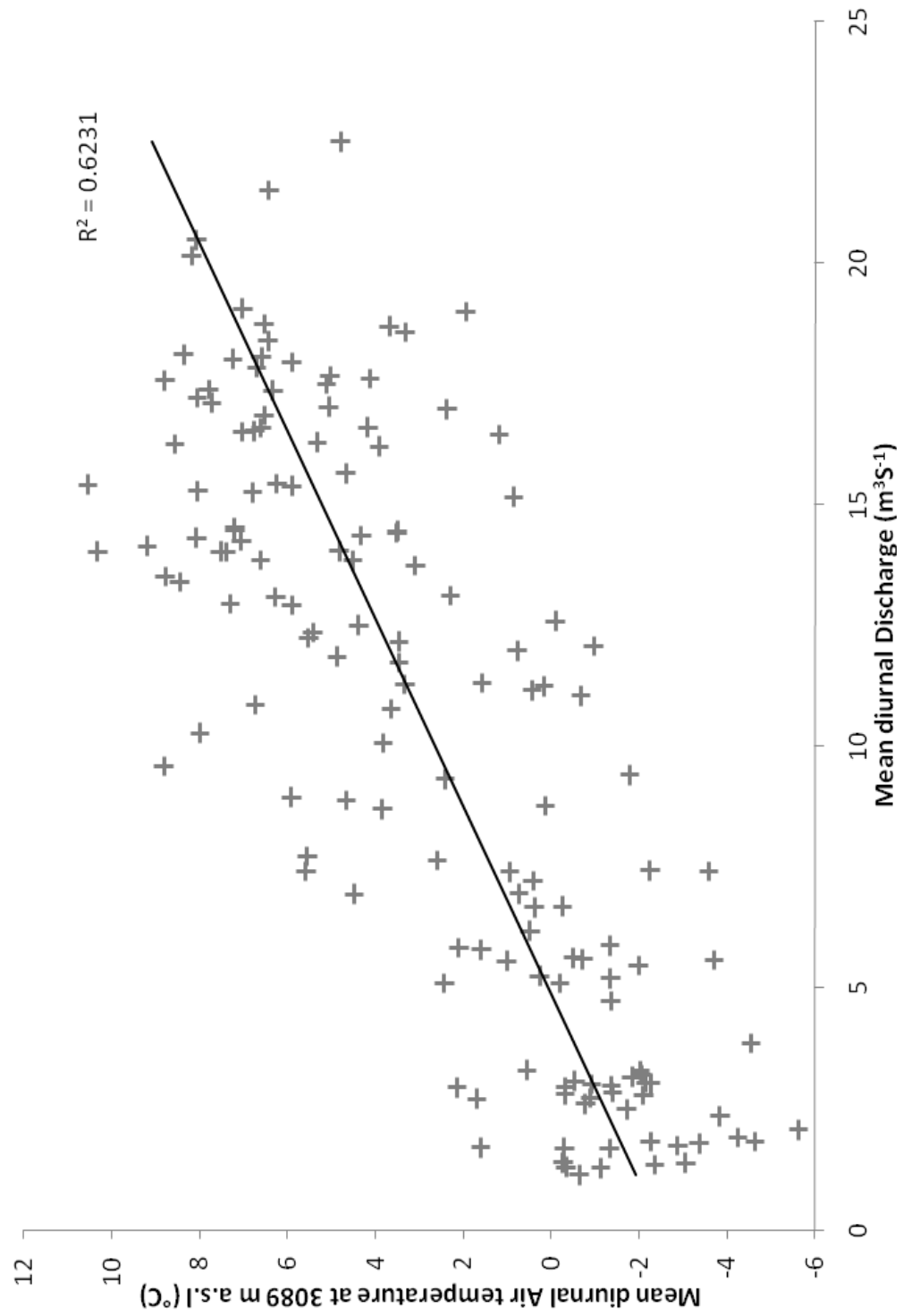
This section is separated in to three phases, (1) a series of plots representing actual measurements which attempt to explain the relationship between air temperature, discharge, ice area availability and the sensitivity of glacier ice below the 0°C air temperature isotherm. (2) A sequence of graphs modelling ice melt runoff from Gornergletscher which explain mean diurnal runoff for summer months and actual discharge is plotted alongside for comparison. A series of modelled runoff distribution plots are illustrated. (3) The model is tuned to scenarios of +1°C, +2°C, +3°C air temperature increase in order to derive a runoff response. For these air temperature scenarios, runoff response from each elevation band will be analysed, and will provide information on distributed runoff response following increased energy availability.

The model was calibrated against actual discharge, with a number of externalities also accounted for during this process. This is a model of limited data availability, and therefore the scope of accuracy may be slightly lower compared to previous studies. Certain parameters not available for input in the model will reduce the chance of simulated runoff shadowing actual discharge from Gornergletscher. The opening graphs displayed (figs.5.1; 5.2) are formed from the original data, and represent relationships between the input parameters.



**Figure 4.1** Mean diurnal air temperature and discharge during the ablation season of 2008.

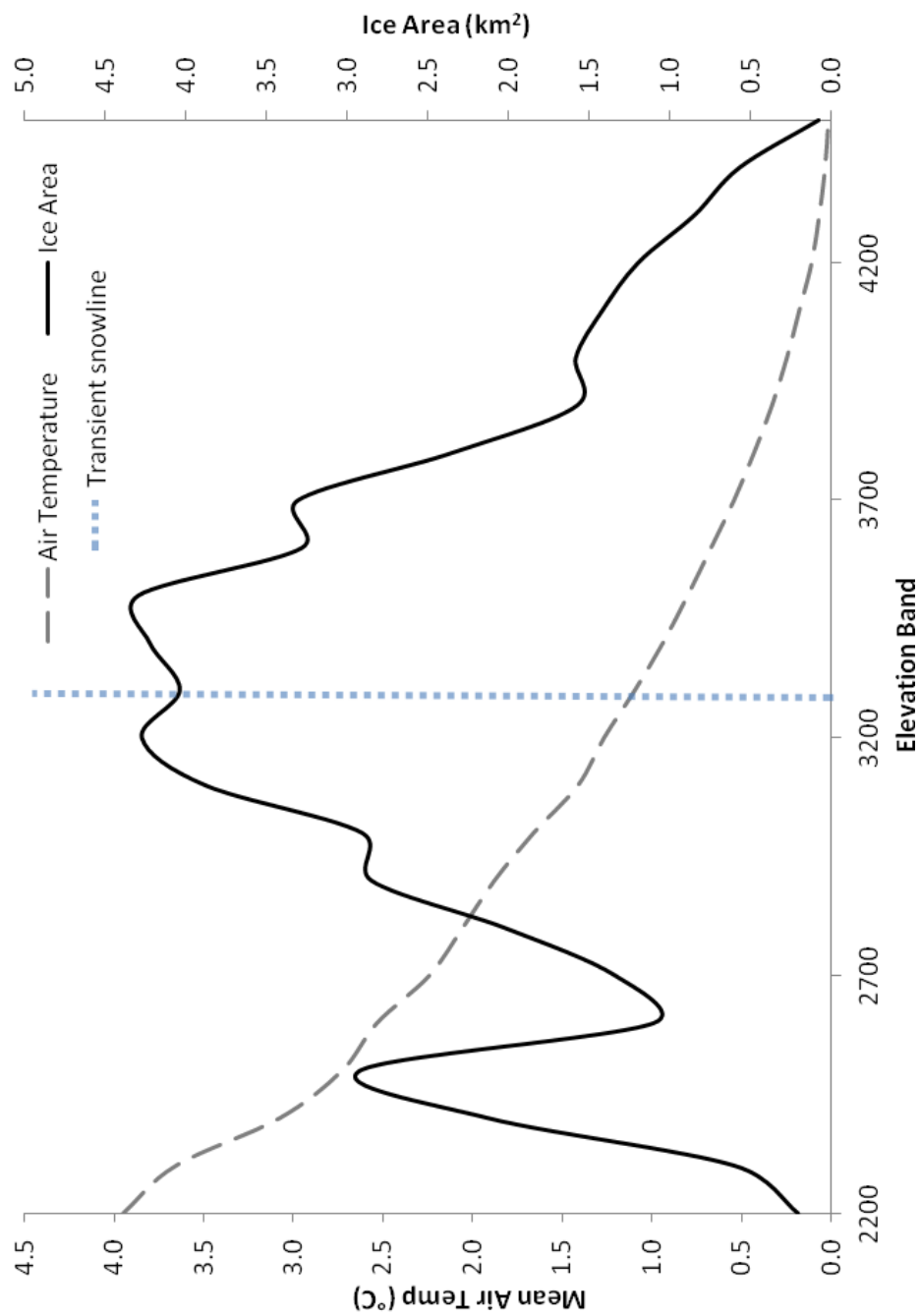




**Figure 4.2** Relationship between mean diurnal air temperature and discharge during the ablation season of 2008.

During summer months peak radiation levels are achieved, this is notable between days 175 – 220 (fig.4.1). Mean daily air temperature plotted in the graph (fig.4.1) was measured at 3300 m a.s.l. During the peak radiation period indicated (day 175-220) air temperature abnormally falls below 0°C for only 24 hours, this indicates the significant proportion of ice melt Gornergletscher is subject to at high elevations, not only at the terminus.

The plot (fig.4.1) shows discharge following the pattern of air temperature, typically there is a slight lapse rate between activity in air temperature and the resulting discharge. Although, generally when air temperature is raised then discharge is enhanced shortly after. Furthermore, the plot indicates that during the initial period (day 127 – 167) when discharge is low compared to later summer that the snowline is still in transit (fig.4.3). However, it is possible the snowline reached its maximum position at approximately day 167, and therefore a greater ice area is exposed which coincides with a sharp increase in air temperature producing peak discharge (fig.4.3).



**Figure 4.3** Mean air temperature for positive degree days at each 100m elevation band, transient snowline maximum and ice area for the basin containing Gornergletscher during ablation season 2008.

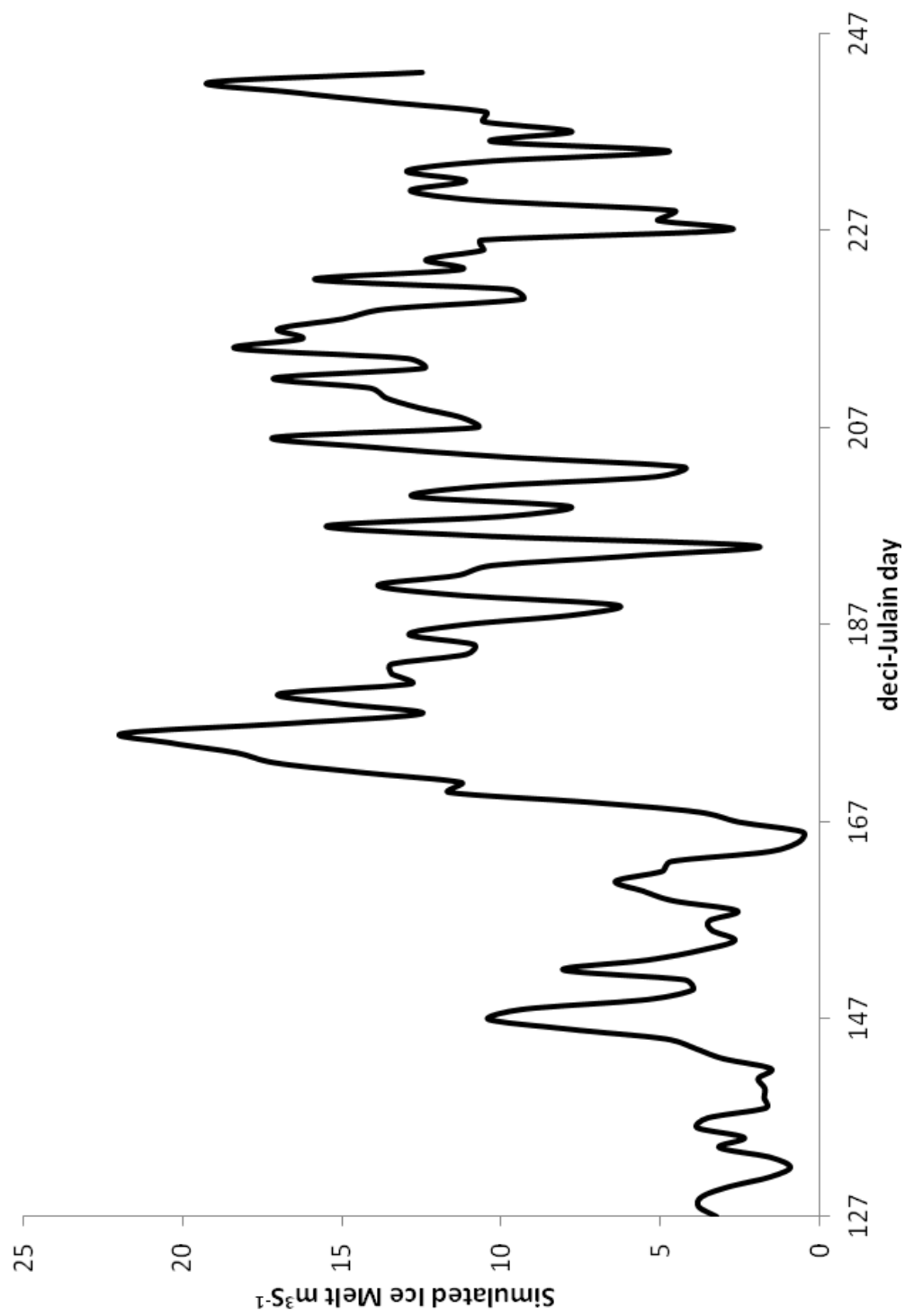
The transient snowline maximum marks the extent to which bare surface ice of the glacier is exposed during ablation season. The maximum snowline position during a given summer results in albedo being lowered between the glacier terminus and the 0°C air temperature isotherm. Albedo of snow and ice is given as an approximate factor of 0.7 and 0.3 respectively; this enhanced sensitivity of the glaciers surface coincides during a period of peak radiation. There is around 1100m in glacier length from terminus to the snowline maximum, and this area is subject to radiation absorbance of 70%. As a result, the model should show greatest melt between 2200-3300 m a.s.l., represents positive degree days, and generates the daily mean at each elevation band for summer months. However, positive air temperatures remain above 1.5°C at elevations beneath the snowline, and this would usually be expected to induce amplified ice melt from a glacierised basin.

During summer months positive air temperatures at low elevations are more frequent, with higher mean diurnal temperatures and a greater ratio of ice to snow area, this is characterised by radiation absorption (albedo of ice). Justifiably, the graph (fig4.3) shows highest ice areas after the 0°C isotherm where positive air temperatures are infrequent.

#### 4.0.1 Modelled ice melt for summer 2008

In order to investigate ice area sensitivity to air temperature and the impact on runoff, a temperature index model was formed, and simulates ice melt draining from the basin containing Gornergletscher for the ablation season of 2008 (fig4.4). Ice melt runoff from Gornergletscher was modelled using a degree day factor of 11.5 (Braithwaite and Zhang, 2000). The model was applied for the period May 6 through September 1, and was based on ice area coverage from 2200 – 4500 m a.s.l for the basin containing Gornergletscher (fig. 4.4).

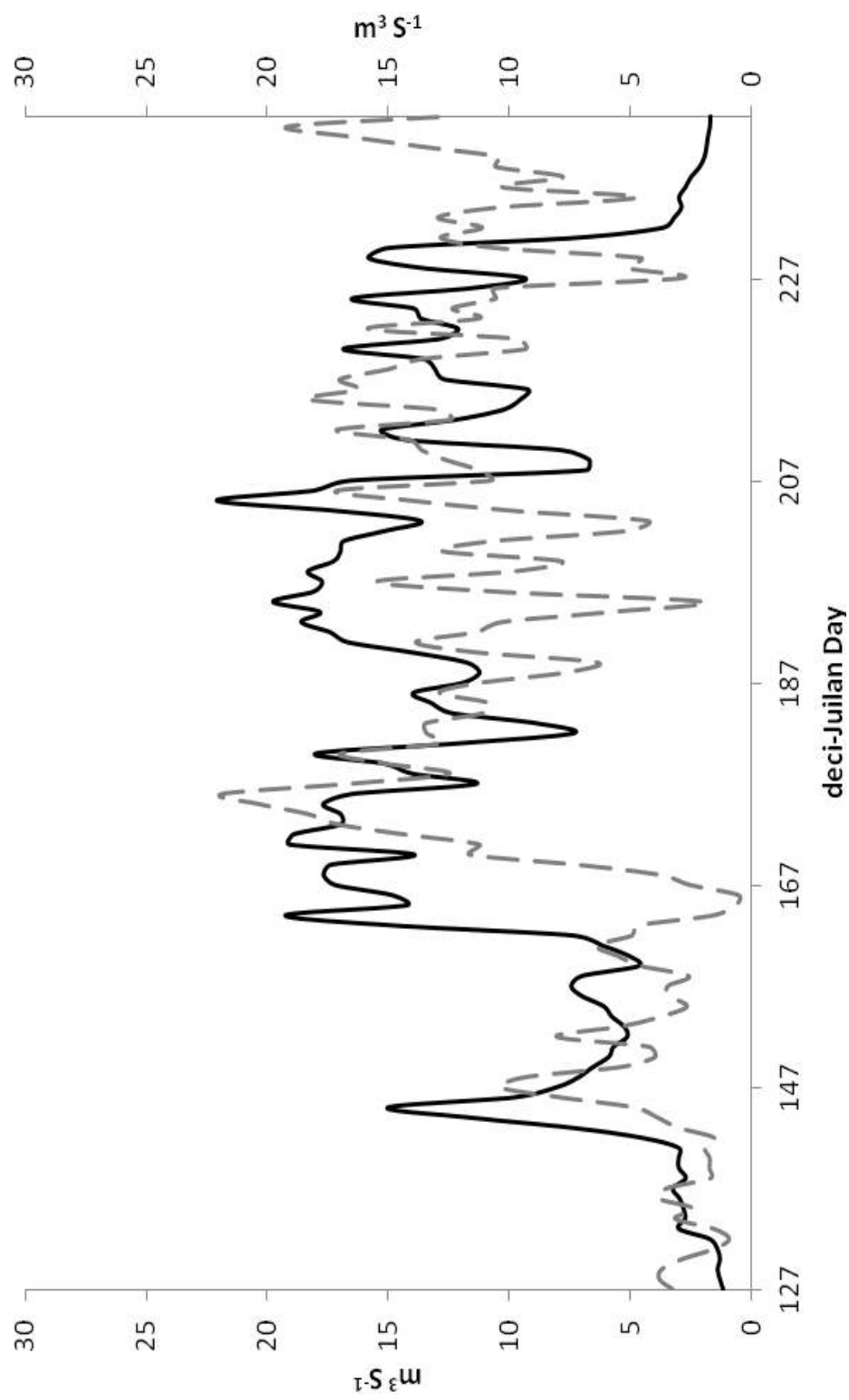
Ice melt contributes the highest portion of summer runoff draining into the Gornera River; therefore, modelled ice melt runoff is plotted alongside actual discharge (fig4.5), and the modelled series should follow measured discharge. This should assist investigation and explanation of deficiencies where the model does not follow actual measurements, and any differences between both series (fig. 4.5) can be clarified.



**Figure 4.4** Simulated mean diurnal ice melt for Gornegletscher during the period of May 6 through September 1.

Modelled ice melt during the initial summer months begins at a relatively low level and then is later raised around day 175 for the duration of summer months. Ice melt is low during May, this is expected because the seasonal snowpack is still being depleted and contributes the main fraction to runoff from basin drainage during May. Transient snowline ascent to higher elevations coincides with the imminent event of peak radiation during July/August. Ice melt is raised by day 175 (June 24) and maintained throughout the summer months in the lead up to maximum radiation and increasing ice area availability in the basin.

Ice melt is a direct and sensitive indicator of temperature fluctuation, and which the temperature index model represents as amplified peaks over shorter periods. Therefore where air temperature is raised it would be expected modelled ice melt will increase between the terminus and 3300 m a.s.l where ice area is available. In the model peak ice melt is achieved during late June, and the transient snowline typically reaches maximum extent at the end of July. Fig.4.5 shows measured discharge with modelled ice melt over summer



**Figure 4.5** Modelled mean daily ice melt (dashed line) and measured daily runoff (solid line) for Gornergletscher during the period of May 6 through September 1.



Measured runoff appears to broadly follow the pattern of simulated ice melt, specifically during early to mid summer months, from 127 - 190. Measured runoff curves react to variance in flow volume lagged around 24 hours behind modelled ice melt flux. The ice melt model does not take in to account time lapse between raised air temperature, the time it takes to melt a parcel of ice from the glacier, and the transit time between melt and gauging station. Measured runoff suggests a parcel of ice melt which is gauged, could have been melted by raised air temperature up to 24 hours earlier e.g. measured discharge shows a ~1 day delay (day 147) behind modelled runoff. The lag between the two series in the plot occurs because the model is forced by air temperature in real time. Flow is measured when it reaches the gauge so discharge can occur up to a day after the water generating flow was melted. The model assumes immediate discharge. The model also assumes instant melt, and any fluctuation is subject to any sudden temperature variance from cumulative elevation values.

Ice melt from the glacier is subject to extended transit time during the early part of the ablation season, and the lag therefore is reduced in later summer months when melt passes through enlarged conduits in the glacier more freely. The conduit system draining melt from Gornergletscher develops continuously during the melt season and reaches peak efficiency in July/August. This is when air temperature is raised and a greater ice area is available for melt, resulting in enhanced flow. Once melt volume is increased, transit time is reduced following widening and expansion of the conduit system. Drainage pathways are elongated and a more rapid transit from melting to gauge is experienced, reducing the lag between modelled melt and measured discharge.

Modelled melt rarely reaches the same peaks as measured runoff. Gauged runoff is contributed to by groundwater, precipitation, snowmelt and ice melt. For this reason higher runoff peaks are recorded for measured runoff than modelled ice melt. Measured runoff and modelled ice melt follow a very similar pattern from day ~130 - 190 when ice area availability is still relatively low but expanding, and melt controlled somewhat by remaining snow cover. It is expected that a greater ice area

available for melt in the basin will induce more frequent runoff variability. When summer progresses, exposed ice area for the basin containing Gornergletscher increases across most elevation zones. Ice covered portions of the basin are less protected against higher levels of energy availability during later summer months.

Between day 165 - 167 (fig 4.5) actual discharge increases from  $5 \text{ m}^3 \text{ s}^{-1}$  to  $20 \text{ m}^3 \text{ s}^{-1}$ , and modelled ice melt also increases from  $1 \text{ m}^3 \text{ s}^{-1}$  to  $22 \text{ m}^3 \text{ s}^{-1}$  during the same period. Modelled ice melt experiences a delayed increase and reaches the same peak as measured discharge around 5 days later. This is during a period of rapid transient snowline retreat, and the exposure of surface ice. Amplification of measured runoff is undoubtedly induced by enhanced air temperature, but also coincides in a time frame of usual summer snowpack melting during a period of increasing radiation. Thereafter actual discharge is maintained throughout summer months at relatively high levels, therefore the peak at day 165 could be a result of both; snowpack depletion and initial summer ice availability during a warm period. Modelled ice melt increases over a longer period, as snowmelt is not accounted for in the model, and although ice area decreases, it is available for melt during periods of raised air temperature.

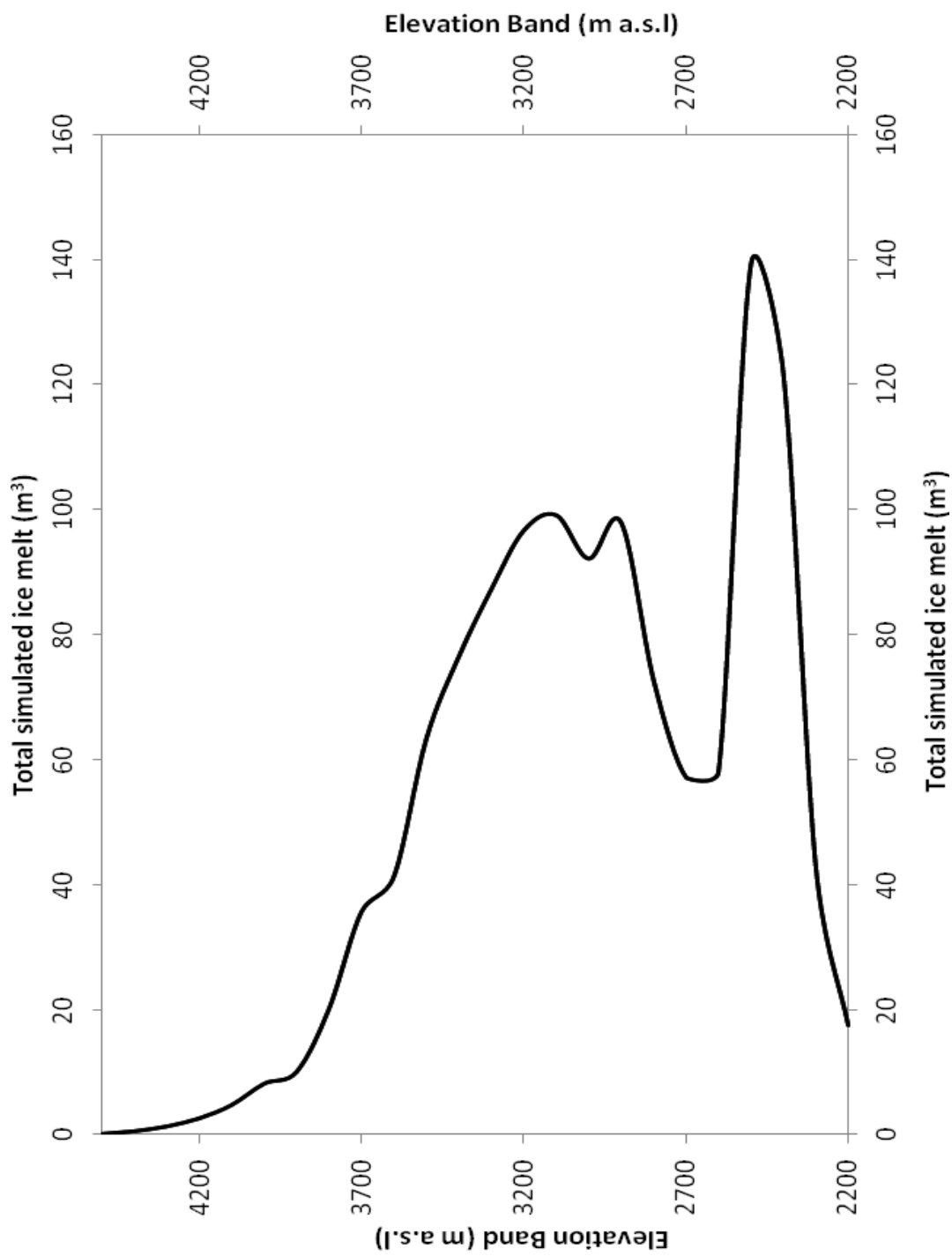
Measured runoff does not follow the same pattern as simulated ice melt during the period between days 190 – 204. Moreover, air temperature shown in fig.4.1 fluctuates between  $0^\circ\text{C}$  and  $8^\circ\text{C}$  during the same period. Modelled ice melt is notably lower than measured discharge during this period but maintains variability, hence flux in air temperature results in lowered volume of ice melt. Between day 190 - 204 an alternative source contributes to measured discharge when ice melt is lowered; Precipitation generally lowers air temperature. Therefore precipitation as rainfall as opposed to snow is considered to have reduced ice melt. Furthermore, air temperature was not lowered enough to induce summer snowfall, and since albedo was unlikely to have been increased, actual runoff was sustained.

Total modelled ice melt from Gornergletscher during the period May 6 through September 1 is  $1245.54 \times 10^6 \text{ m}^3$ . Total measured discharge for the basin containing Gornergletscher during the period May 6 through September 1 was  $1296.97 \times 10^6 \text{ m}^3$ . Total measured runoff was greater than the modelled by  $51.42 \text{ m}^3$ . The difference between the runoff totals indicates a quantity of runoff that is gauged which is

unaccounted for in the model e.g. groundwater, rainfall, snowmelt. Therefore, this difference of 3.96% suggests measured runoff from the basin containing Gornergletscher is contributed by other sources, whereas the remaining 96.04% of measured discharge is contributed by ice melt from Gornergletscher.

#### 4.0.2 Modelled ice melt for elevation bands

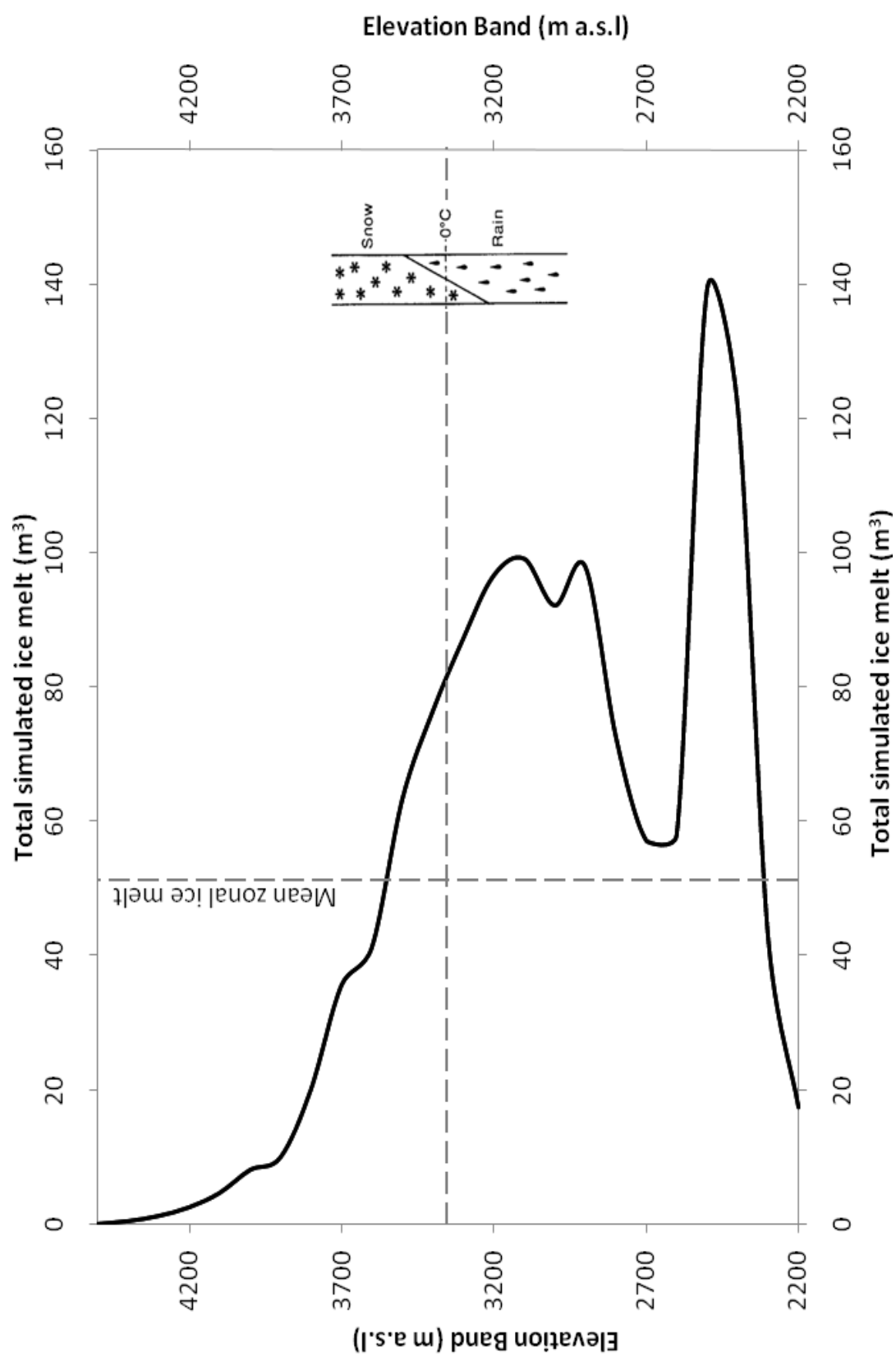
The following model (fig.4.6) shows total ice melt runoff by elevation band (100m bands) from 2200 – 4500m.a.s.l from Gornergletscher during the period May 6 through September 1. The model shows ice melt runoff from each elevation band based on air temperature and a lapse rate factor of 0.6°C, and highlights the most productive bands. Individual elevation zones influence the hydrological regime of the Gornera River during summer months, hence certain 100m bands generating >10% of overall runoff from the basin containing Gornergletscher.



**Figure 4.6** Modelled total ice melt by elevation band draining from Gornegletscher during the period May 6

Ice melt is relatively low around the glacier terminus; this is expected due to low ice area availability, despite the highest air temperature being experienced in this zone. Subsequently ice melt production is rapidly increased between 2300 – 2800 m a.s.l. The elevation band 2500 – 2600 m a.s.l. generates most ice melt across the entire basin, with ice melt becoming reduced between 2600 – 2800 m a.s.l. Increased melt runoff over a large area is then experienced between 2800 – 3500 m a.s.l., with these elevation bands contributing 55.02% of overall ice melt from Gornergletscher. Moreover, from 3500 – 4500 m a.s.l, ice melt production begins to gradually decrease between 3500 and 3900, with minimal/limited ice melt between 3900 and 4500 m a.s.l.

Ice melt runoff is greatest from elevation bands at low to mid altitudes, and this is offset by the 0 °C air temperature isotherm at ~3300 m a.s.l. The majority of elevation bands producing higher than average volumes of ice melt are in the zone below the maximum transient snowline (fig.4.7).



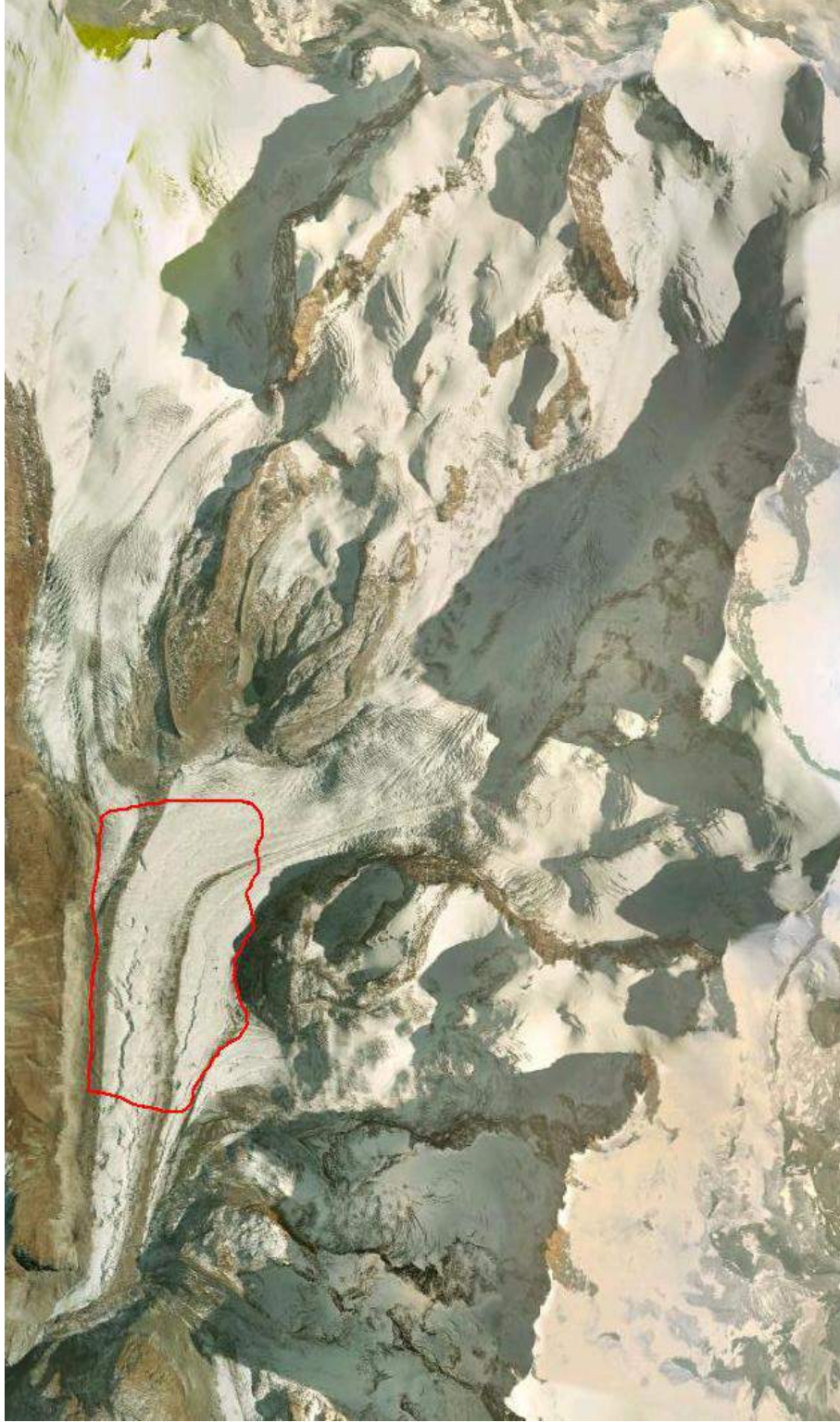
**Figure 4.7** Modelled total ice melt by elevationband, interaction with 0°C isotherm band ice melt production in relation to the mean

All elevation bands, with the exception of the terminus produce ice melt volumes exceeding the mean until the 0°C air temperature isotherm (table 4.1). Reduced ice melt at 3300 m a.s.l is offset by maximum elevation of the snowline, limited ice area exposure and minimal energy available for melt.

**Table 4.1** Total simulated ice melt and percentage contribution for each elevation band of the basin containing Gornergletscher, ablation season 2008.

m a.s.l	<b>2200</b>	<b>2300</b>	<b>2400</b>	<b>2500</b>	<b>2600</b>	<b>2700</b>	<b>2800</b>	<b>2900</b>	<b>3000</b>
Total Q (x 10 <sup>6</sup> m <sup>3</sup> )	17.41	42.79	121.78	139.21	57.98	57.12	72.69	97.92	92.13
% Contribution	1.39	3.43	9.77	11.18	4.65	4.58	5.83	7.86	7.39
m a.s.l	<b>3100</b>	<b>3200</b>	<b>3300</b>	<b>3400</b>	<b>3500</b>	<b>3600</b>	<b>3700</b>	<b>3800</b>	<b>3900</b>
Total Q (x 10 <sup>6</sup> m <sup>3</sup> )	99.08	96.62	87.24	76.44	63.31	41.24	35.59	20.08	9.97
% Contribution	7.95	7.75	7.00	6.13	5.08	3.31	2.85	1.61	0.80
m a.s.l	<b>4000</b>	<b>4100</b>	<b>4200</b>	<b>4300</b>	<b>4400</b>	<b>4500</b>			
Total Q (x 10 <sup>6</sup> m <sup>3</sup> )	8.07	4.65	2.51	1.22	0.46	0.05			
% Contribution	0.64	0.37	0.20	0.09	0.03	0.004			

Ice area distribution for the basin containing Gornergletscher is expected to vary at each elevation zone. Basin hypsometry and area coverage of the basin is extended within several elevation bands, however some zones have lower area coverage, as a result, ice portion coverage is limited; ice melt runoff from elevation bands is controlled by basin hypsometry, e.g. ice distribution at 2500 - 2600 m a.s.l (fig.5.8) contributes a large proportion of Gornergletscher below the 0°C air temperature isotherm.

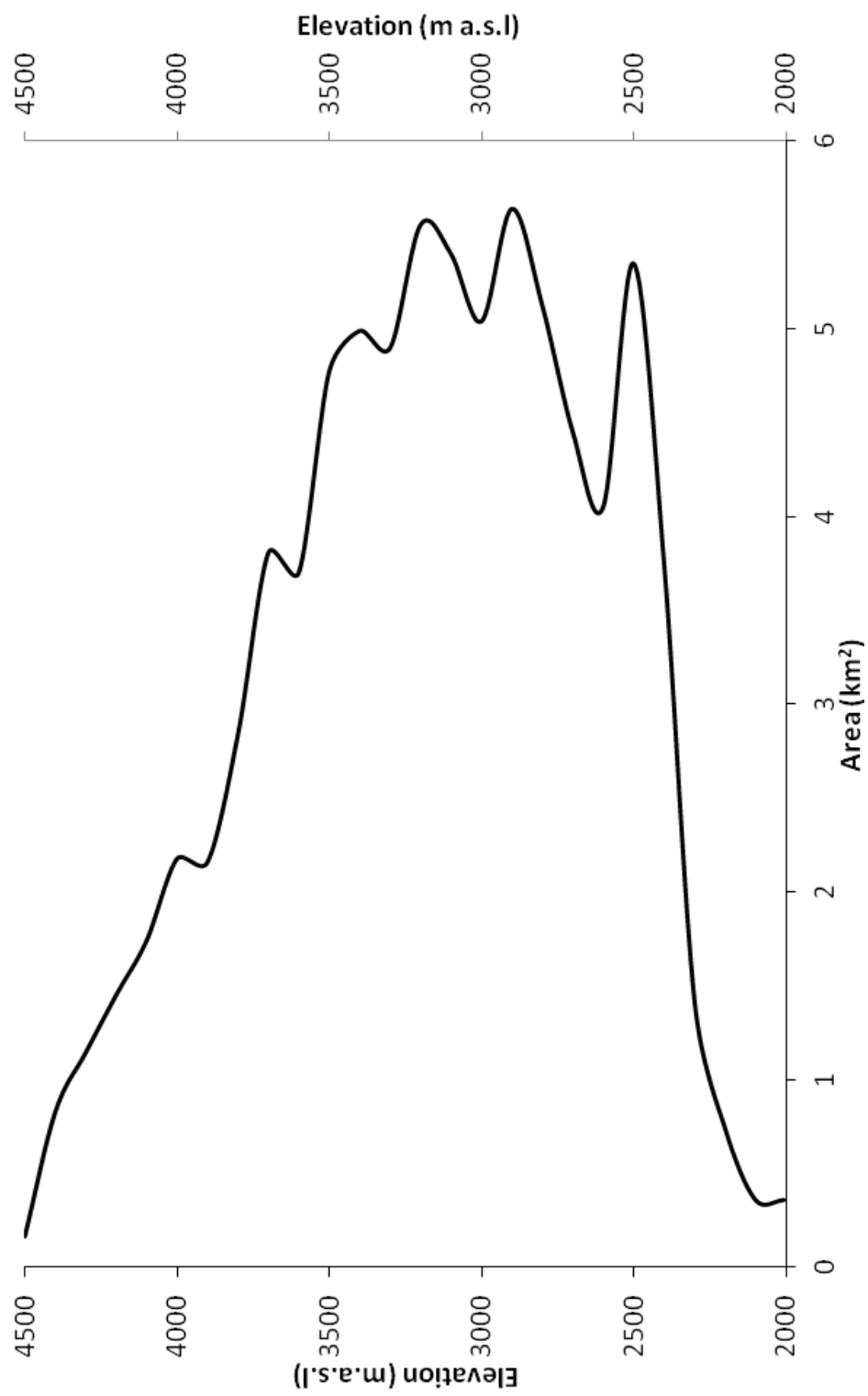


**Figure 4.8** Outline and extent of elevation band 2500 - 2600 m a.s.l., the band generating greatest ice melt volume during Ablation season 2008.



Peak volumes of ice melt contribution would be expected at elevation zones with a basin area distribution higher than the mean, and above the 0°C air temperature isotherm. The band 2500 - 2600 m a.s.l spans 5.34 km<sup>2</sup>, thus 6.53% of total basin area is distributed in this 100m elevation band (fig.5.9). The mean basin area distribution per-elevation band is 3.14 km<sup>2</sup>, and once the mean is exceeded for an elevation band, then ice area available for melt is increased at altitudes below 3300 m a.s.l.

Moreover, Gornergletscher is an elongated, wide, flat glacier compared to neighbouring Findelengletscher. Hence large portions of the basin with only slight gradient change being distributed in individual bands; thus to a large extent, basin hypsometry determines ice melt runoff from Gornergletscher (fig4.8). The elevation band 2500 – 2600 m a.s.l (fig 4.8) exemplifies a low to mid elevation band with a high basin area distribution and ice area, and is representative of the ‘flat’ profile of Gornergletscher.

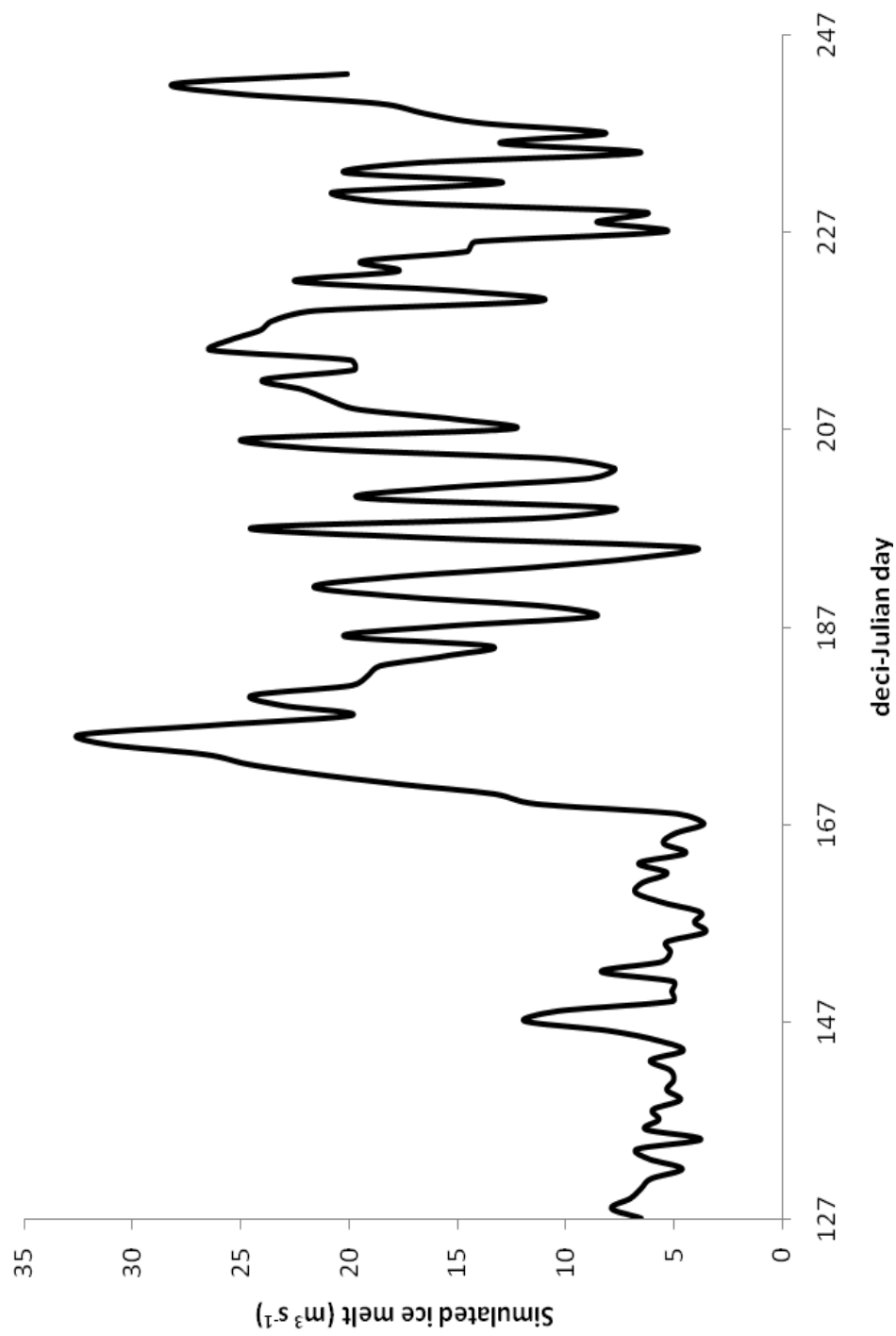


**Figure 4.9** Hypsometry of the basin containing Gornegletscher from 2000 - 4500 m a.s.l

Ice area in each zone is controlled by the distribution of basin area (fig4.9) for each elevation band. Therefore, the zones with greatest ice areas distribution at lower elevations, (i.e. below the 0°C air temperature isotherm) would be expected to produce enhanced ice melt.

#### 4.0.3 Model tuning to air temperature for summer 2008

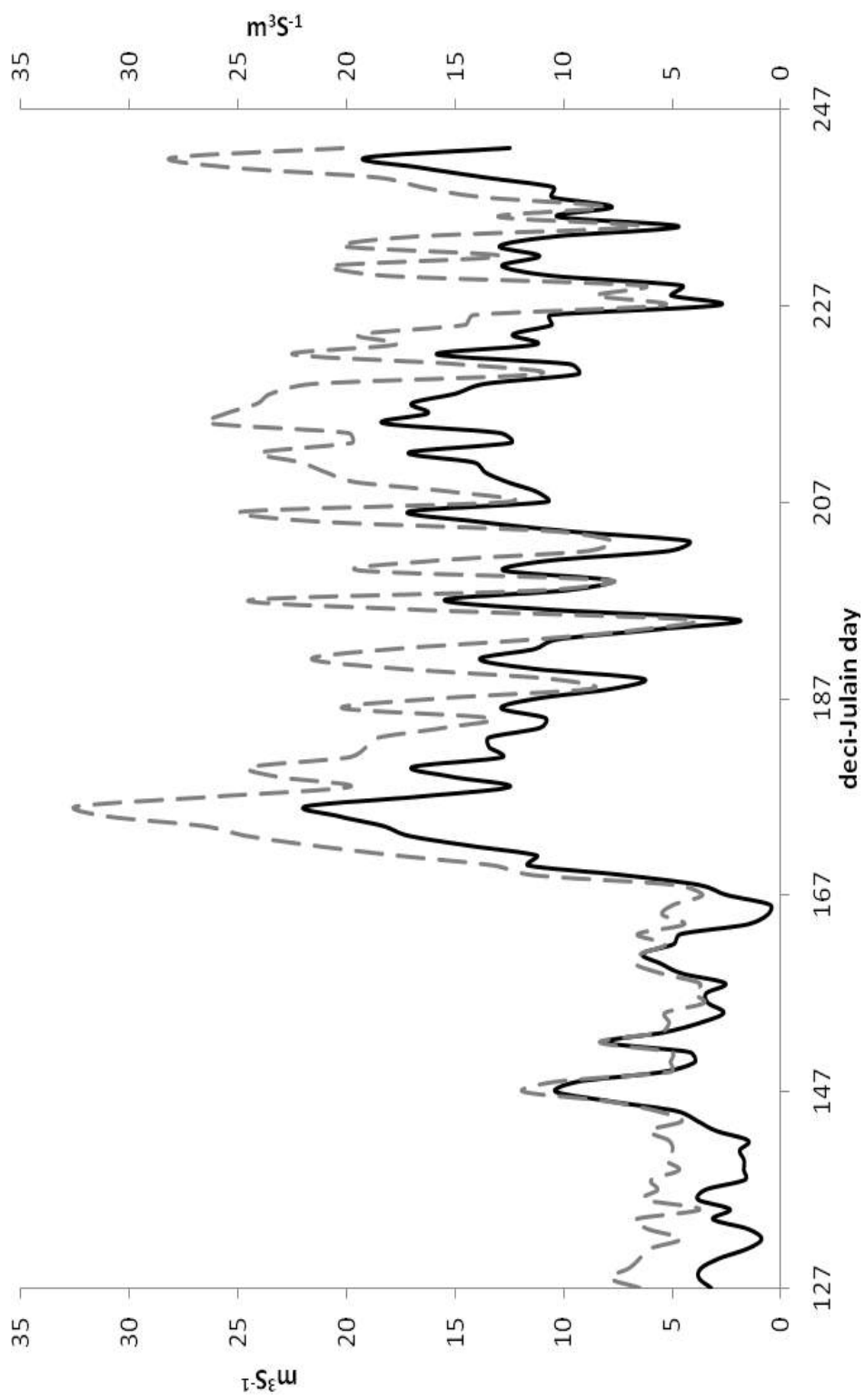
A positive annual mass balance could go some way to compensating the effects of a 1°C rise in air temperature for Gornergletscher to a point (fig.5.10). However due to predominant basin distribution at low elevations and abundant ice area below 3300 m a.s.l, and additional snowline transit should certainly see an increase in modelled ice melt between 2800 - 3200 m a.s.l. The frequency of positive degree days reduce with elevation, and therefore frequency should increase significantly below 3300 m a.s.l at zones with high basin area share.



**Figure 4.1.1** Mean daily modelled ice melt for +1°C rise in air temperature during ablation season 2008 for the basin containing Gornegletscher.

The model was tuned to a +1°C rise in air temperature, which was expected to significantly increase ice melt runoff from Gornergletscher. Modelled ice melt was raised by 24.8% following an air temperature increase of 1°C; the original modelled ice melt peaked through the summer months at ~15 - 18 m<sup>3</sup> s<sup>-1</sup>, whereas a 1°C air temperature increase results in modelled ice melt peaks of ~22 - 25 m<sup>3</sup> s<sup>-1</sup>.

During the period between day 127 – 167, modelled ice melt is relatively low with several small peaks. However the abrupt increase at day 168 indicates an increase from ~4 – 34 m<sup>3</sup> s<sup>-1</sup>, following the same pattern as original modelled ice melt with a greater runoff magnitude. The scale of ice melt variability is increased with a 1°C rise in air temperature, and the difference between mean daily melt rates is amplified. It is expected that following raised summer air temperatures the glacier becomes even more sensitive to change from other parameters. Day-to-day irregular runoff patterns in the Gornera River could be expected, as a result of enhanced mean summer air temperatures of +1°C. The 1°C tuned model follows a corresponding pattern to the original model (fig.5.11); although the increased air temperatures do not have a significant or immediate effect on ice melt until around day 168.



**Figure 4.1.2** Mean daily modelled ice melt (solid line) and +1°C rise simulation (dashed line) during ablation season 2008 for the basin containing Gornergletscher.

In the model (fig4.1.2) when melt suddenly decreases, the +1°C air temperature scenario descends to a similar runoff level e.g. around day 195, 200 and 234. This suggests during periods when ice melt is reduced following low air temperatures, enhanced mean daily warming has little effect on runoff, possibly due to the effect of another parameter such as snowfall/rainfall. The influence of air temperature on ice melt is lessened during periods of precipitation of snow. Amplified ice melt from raised air temperatures of +1°C during mid-summer would potentially be counteracted by summer snowfall and/or rainfall precipitation.

Overall the +1°C model (fig4.1.2) indicates that during days of amplified air temperature greater runoff is generated. Runoff becomes more amplified during peak air temperatures as opposed to periods of lower runoff. Additionally, this is likely to generate a greater difference between the original model and the +1°C model. Air temperature regulates ice melt runoff more effectively in mid to late summer months. This is because an increased ice area is exposed to radiation following the snowline reaching its maximum summer position.

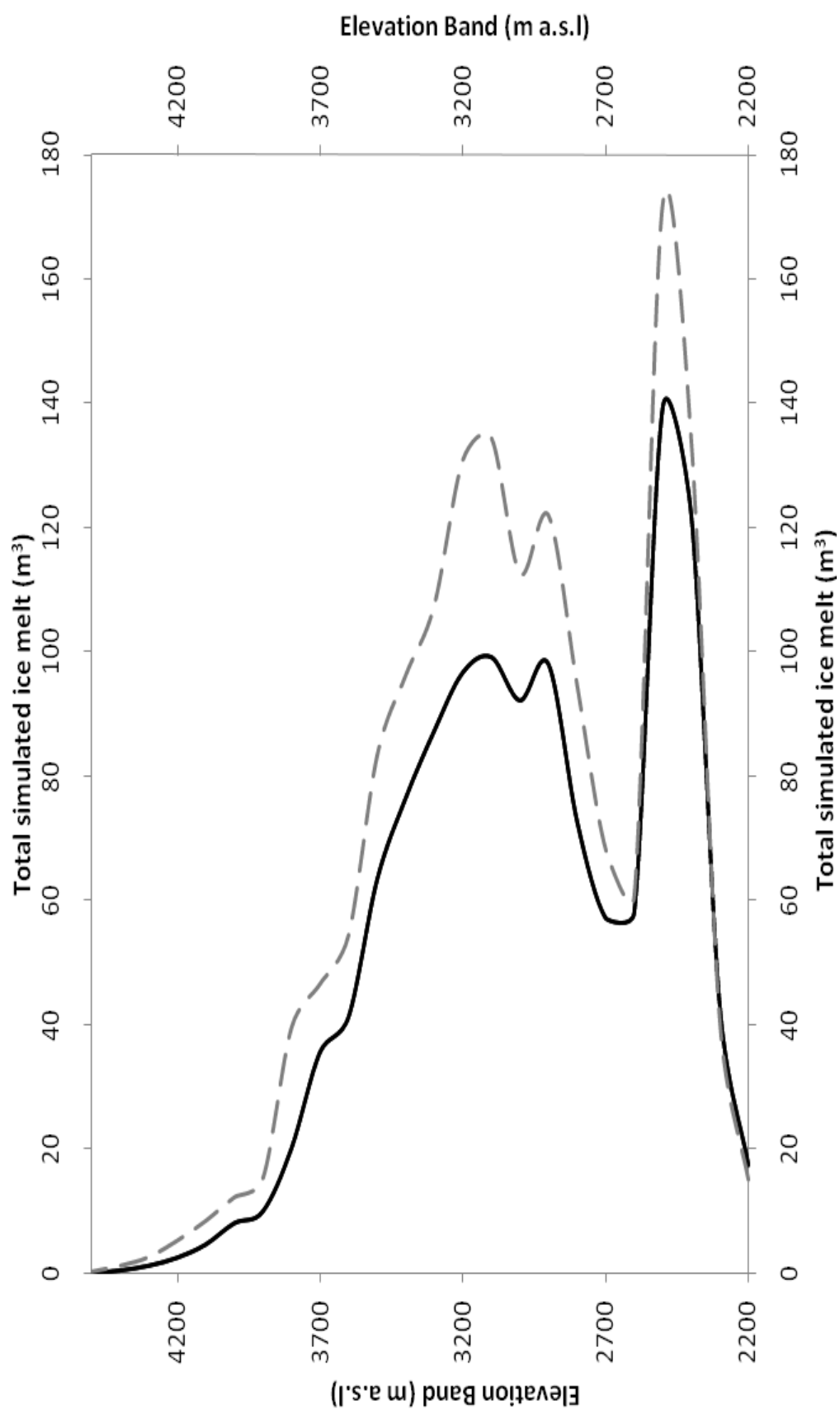
Raised mean daily air temperatures appear to have a relatively insignificant impact during early summer months. However, for the most part of May, ice melt runoff is more than 100% greater following +1°C increase. Typically during May air temperature is comparatively low and ice area availability is low; therefore during May, a +1°C rise would have greatest influence at the terminus where snow cover has been melted away. This would be on a small scale relative to ice melt through other months, and during May the glacier could be most sensitive to air temperature increases.

Modelled ice melt following a +1°C rise in air temperature (fig4.1.3) is expected to be increased most at elevation zones below the summer snowline maximum. Ice melt contribution following to a +1°C increase is likely to be mirrored in elevation bands which already generate highest rates of summer ice melt.

These low to mid elevation bands are typically characterised by greatest ice area distributions and therefore contribute most melt, with highly elevated bands beginning

to produce larger volumes of ice melt, resulting from a +1°C rise in air temperature which would raise the position of the snowline by ~166 m a.s.l. (fig4.1.3).

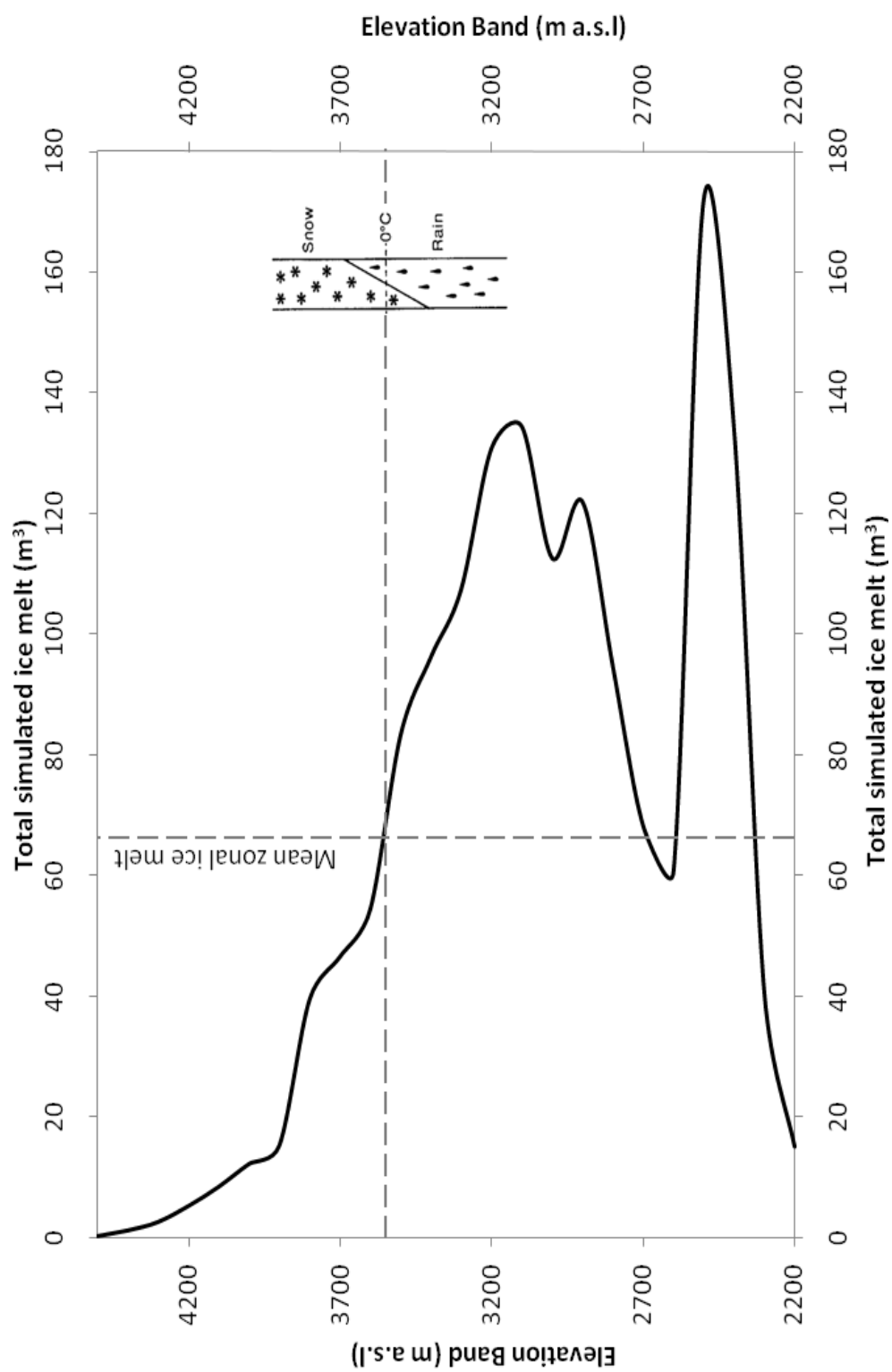




**Figure 4.1.3** Modelled total ice melt (solid line) and +1°C scenario (dashed line) by elevation band draining from Gornergletscher during the period May 6 through September 1.

Ice melt is increased most in the zone 3100 – 3200 m a.s.l following a 1°C rise in air temperature. Ice melt is enhanced at 3100 – 3200 m a.s.l by 35.6% the greatest change of all zones. This elevation band has the second largest basin distribution and second largest ice area below the transient snowline. Although 3100 – 3200 m a.s.l has the largest percentage increase, 2500 – 2600 m a.s.l contributes greatest the proportion of ice melt.

Elevation zone 3100 – 3200 m a.s.l is most sensitive to a +1°C rise in air temperature for the basin containing Gornergletscher (fig.4.1.3). The transient snowline will ascend through ~1.5 elevation zones following warmer summer air temperatures; snow cover will melt and bare ice is exposed, resulting in the absorption of radiation to 70%.



**Figure 4.1.4** Modelled total ice melt by elevation band, interaction with 0°C isotherm and band ice melt production in relation to the mean for a 1°C air temperature increase scenario.

Mean ice melt runoff by elevation band increases from 51.9 m<sup>3</sup> to 64.7 m<sup>3</sup> following an air temperature increase of +1°C. Ascent of the transient snowline to 3500 m a.s.l results in the albedo being lowered from 0.8 to 0.3 across more than 50% of the basins glaciated area. The more air temperature is raised, the less snow area coverage there is in the basin, and as heat energy increases then the 0°C isotherm becomes more elevated and rain falls over a greater number of elevation bands than snowfall. This in turn has implications on the runoff response from the glacier.

Once air temperature for the ablation season is increased by +1°C, then the frequency of positive degree days increases for each elevation band. Day-to-day sustained melting from raised air temperatures coincides with the exposure of mid- elevation bands of the glacier; such bands, have the greatest ice area availability in the basin (table 4.2). As positive degree day frequency increases, mid-elevation band contribution could multiply, as melting off of snow cover reveals extensive ice areas.

**Table 4.2** Matrix of elevation zones and their ice areas in relation to the amount of positive degree days for a +1°C rise in air temperature scenario. Green; low, yellow; moderate, red; high, contribution to ice melt.

Ice Area (km <sup>2</sup> )	Amount of Positive Degree Days						
	15-30	30-45	45-60	60-75	75-90	90-105	105-120
0-1	4400/ 4500	4300					2200/ 2300
1-2		4200	4000/ 4100	3900			2600/ 2700
2-3				3800			2400/ 2500/ 2800/ 2900/ 3000
3-4				3700	3600		3100
4-5						3500	3200/ 3300/ 3400

Table 4.2 shows that once summer air temperatures are increased, ice melt from mid-elevation bands of the basin are likely to increase, following more frequent positive degree days. The grey-shaded cell represents the elevation bands expected to contribute highest proportion of ice melt. The matrix is based on a +1°C rise in air temperature, but such can be generated for any air temperature scenario. In the event

mean air temperature decreased, more elevation bands in the matrix would become yellow/green, and enhanced heat energy would increase the quantity of red bands in the matrix.

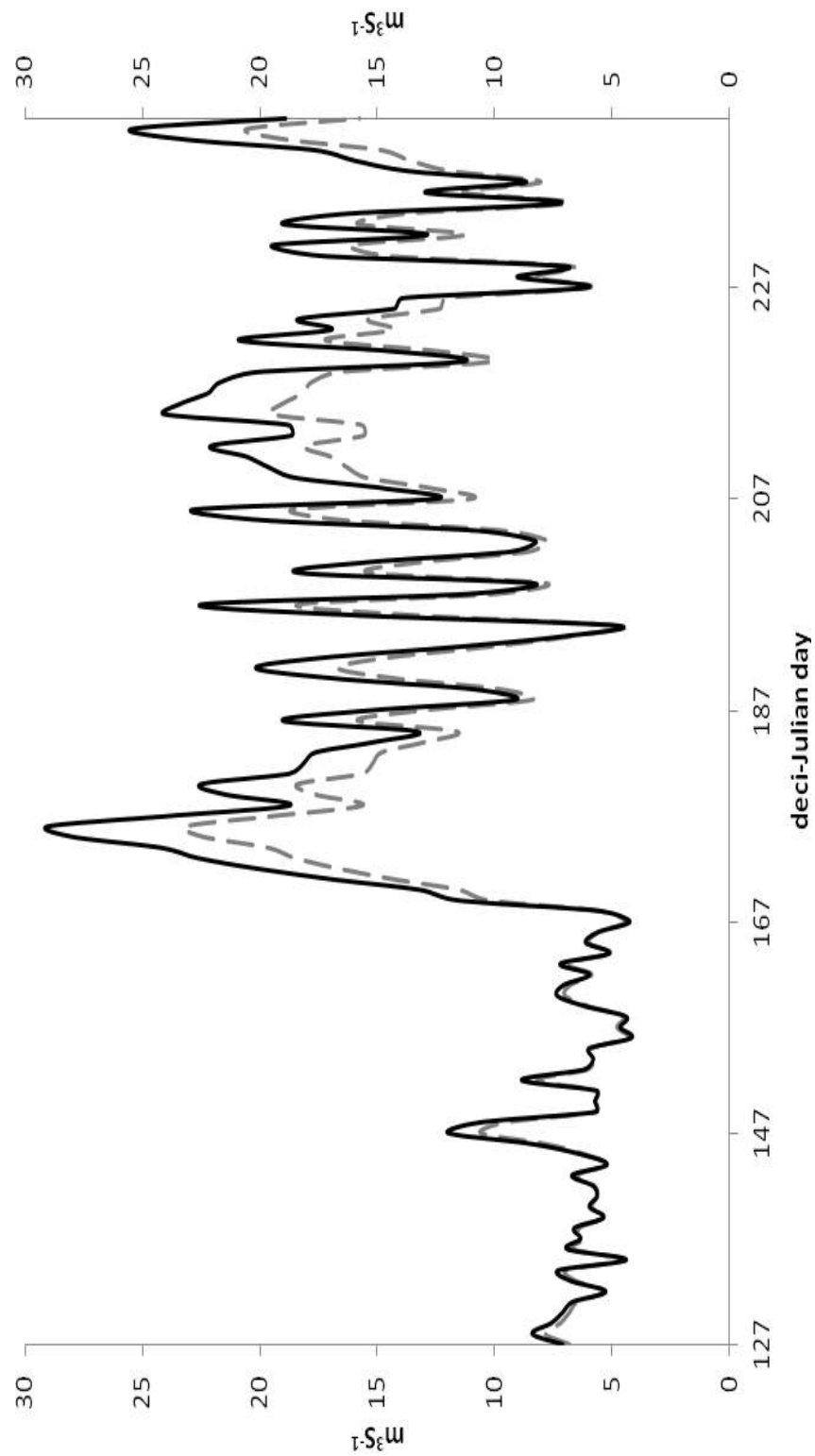
#### 4.0.4 Modified simulation to increased air temperature and reduced ice area

The temperature index model was modified for a second and third time in order to gauge the response of ice melt to reduced ice area as a result of raised air temperature. The model is computed to increase air temperatures to +2°C and +3°C and reduce ice areas of 20% and 40% for the +2°C and +3°C models respectively (fig 4.1.5). The response of ice melt to changes in available energy and ice areas are calculated over time and over elevation bands for comparison with measured runoff and the original runoff model. It is expected that the rise in air temperature for the 2°C model with a 20% ice area reduction will initially amplify ice melt (fig. 4.1.6). In late July/August most ice melt is likely to be produced following a +2°C increase; because the transient snowline ascends higher, albedo is reduced over a greater area, and a 20% ice area reduction will largely be insignificant at the mid-elevation zones ~2900 – 3500 m a.s.l where ice area is greatest.

The model is also modified to a +3°C increase and a 40% decrease in ice area (fig4.1.7), and it is likely ice melt will be lowered in this model throughout the summer and daily runoff magnitude will become less variable. A reduced ice area in the model of 40% is expected to have more influence on the response of ice melt rather than amplified air temperature. Controlled quantities of ice melt are likely to be subject to the quantity of ice portions in the basin.

Ice melt from elevation bands should be modified in the basin, deviating from the original spatial melt model. It is probable that ice melt at mid-high elevations in the 2°C and 3°C models will be increased, although at lower elevations from the terminus to around 2700 m a.s.l melt should be limited and possibly lowered from the original model. This is because even though air temperatures are much higher there is greatly reduced ice area to contribute to sustained high runoff. Ice melt from elevation bands should be raised in the 2°C model for most bands, however the 3°C spatial model

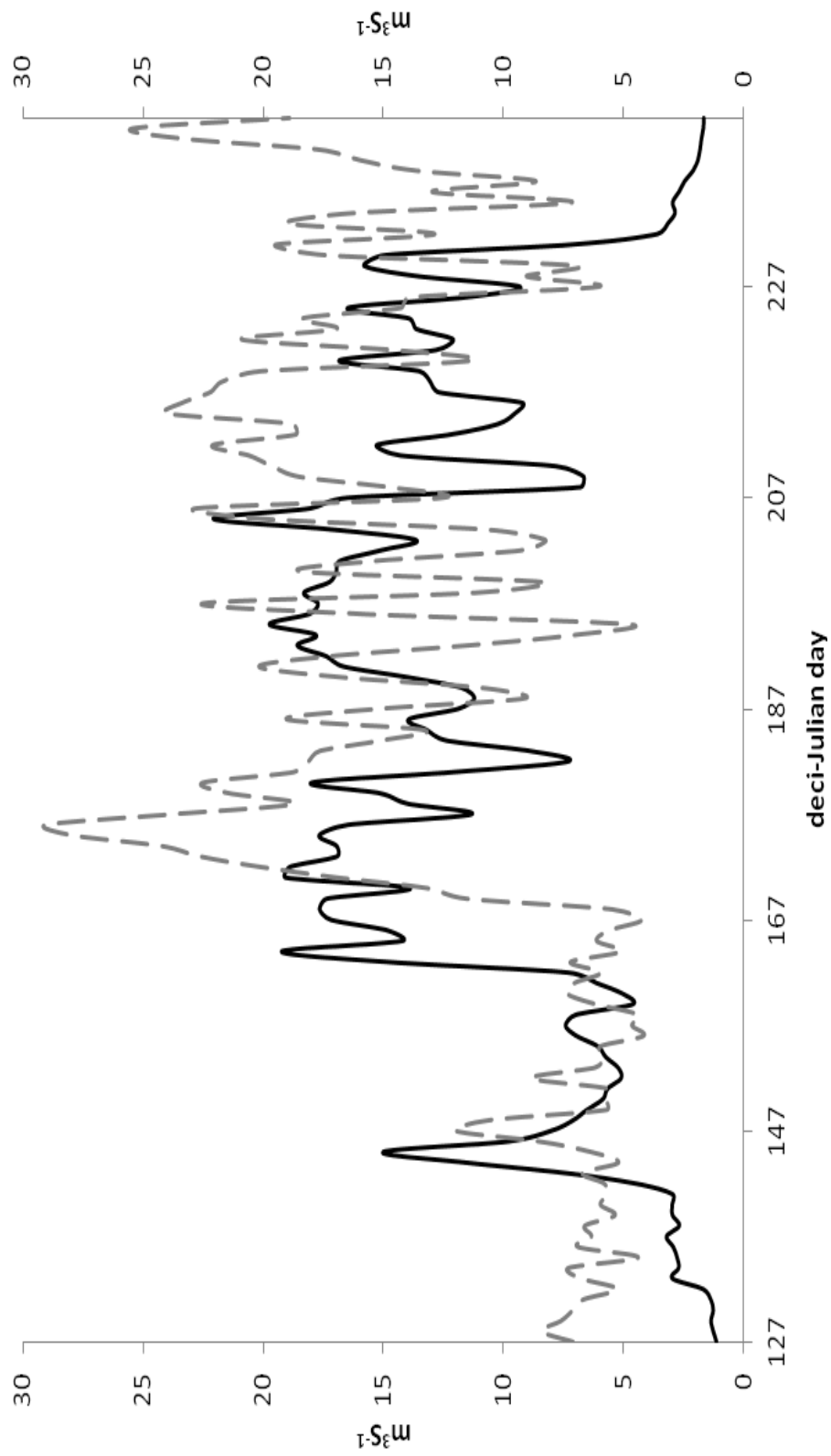
should show some negative values compared to the original model. The purpose of the two additional spatial models is to investigate the relationship between climate, direct runoff response and the influence on ice area.



**Figure 4.1.5** Mean daily modelled ice melt for a +2°C (solid line) and 3°C (dashed line) rise scenario, based on ablation season 2008 for the basin containing Gornergletscher.

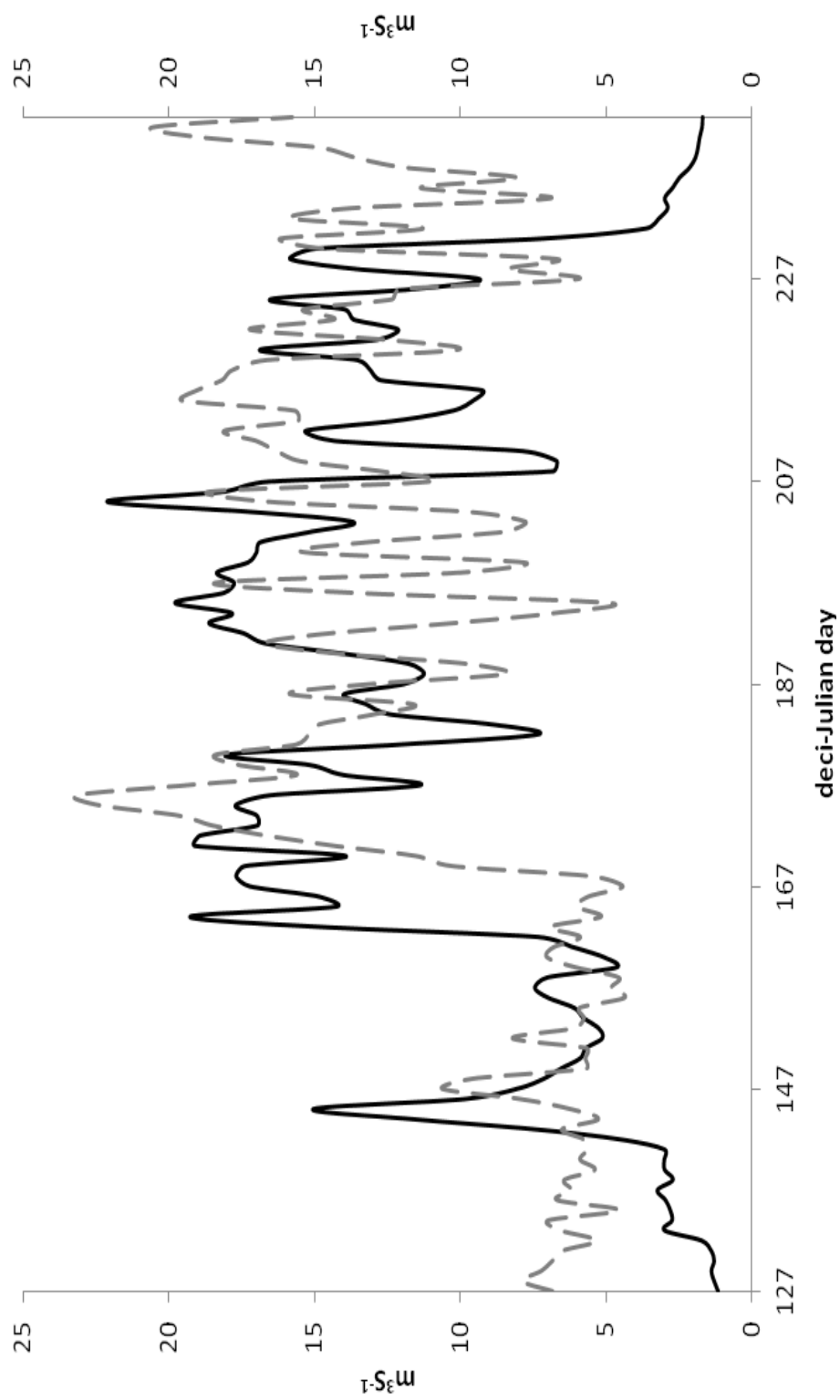
The two series (fig.4.1.5) show that reducing ice area as air temperature increases then magnitude and variability also decrease. Halving the total ice area from -20% to -40% by a  $+1^{\circ}\text{C}$  increase offsets ice melt magnitude during a period of heat energy availability and largely exposed ice surfaces that remain between 2900-3800 m a.s.l. Melt during the summer in the  $3^{\circ}\text{C}$  model almost reflects the original ice melt model, but the  $3^{\circ}\text{C}$  model does indicate glacier wastage in such conditions. The  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$  models (fig4.1.6 and fig4.1.7) are modified to ice areas that reduce by 100% per  $1^{\circ}\text{C}$  increase, so every  $+1^{\circ}\text{C}$  increase would reduce ice area by 100% of its percentage for the  $1^{\circ}\text{C}$  before it, thus  $2^{\circ}\text{C}$  and  $3^{\circ}\text{C}$  20% and 40% respectively.

In addition, the magnitude of ice melt would generally be much greater, and of higher frequency in daily melt, because the basin remains 80% glacierised from its original state with increased heat energy. The  $+3^{\circ}\text{C}$  model is expected to generate ice melt on a similar scale to the regime of actual discharge, therefore the  $+3^{\circ}\text{C}$  model and original melt model induce runoff proportionate to ice area availability.



**Figure 4.1.6** Mean daily modelled ice melt (solid line) and +2°C rise simulation (dashed line) during ablation season 2008 for the basin containing Gornegletscher.

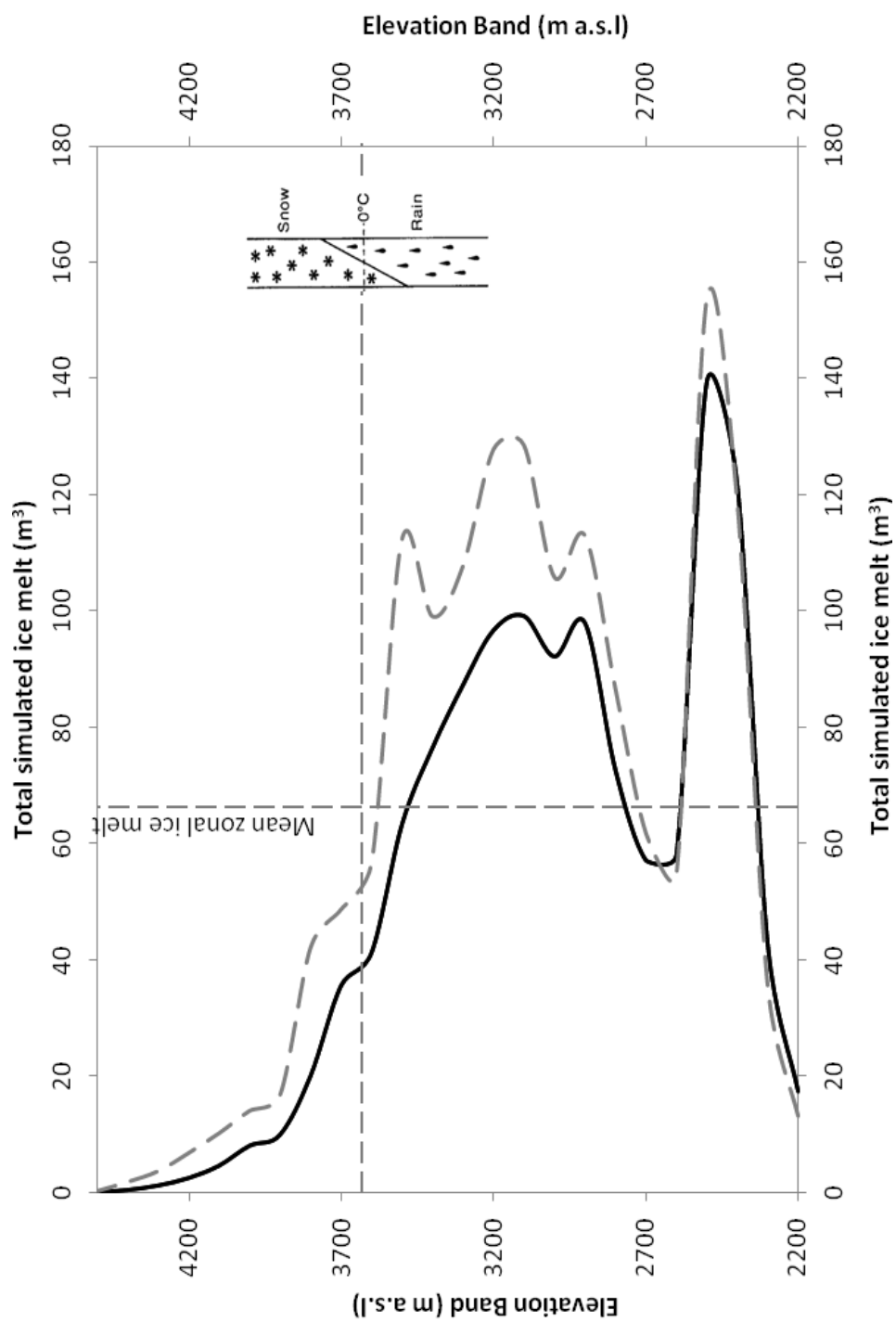




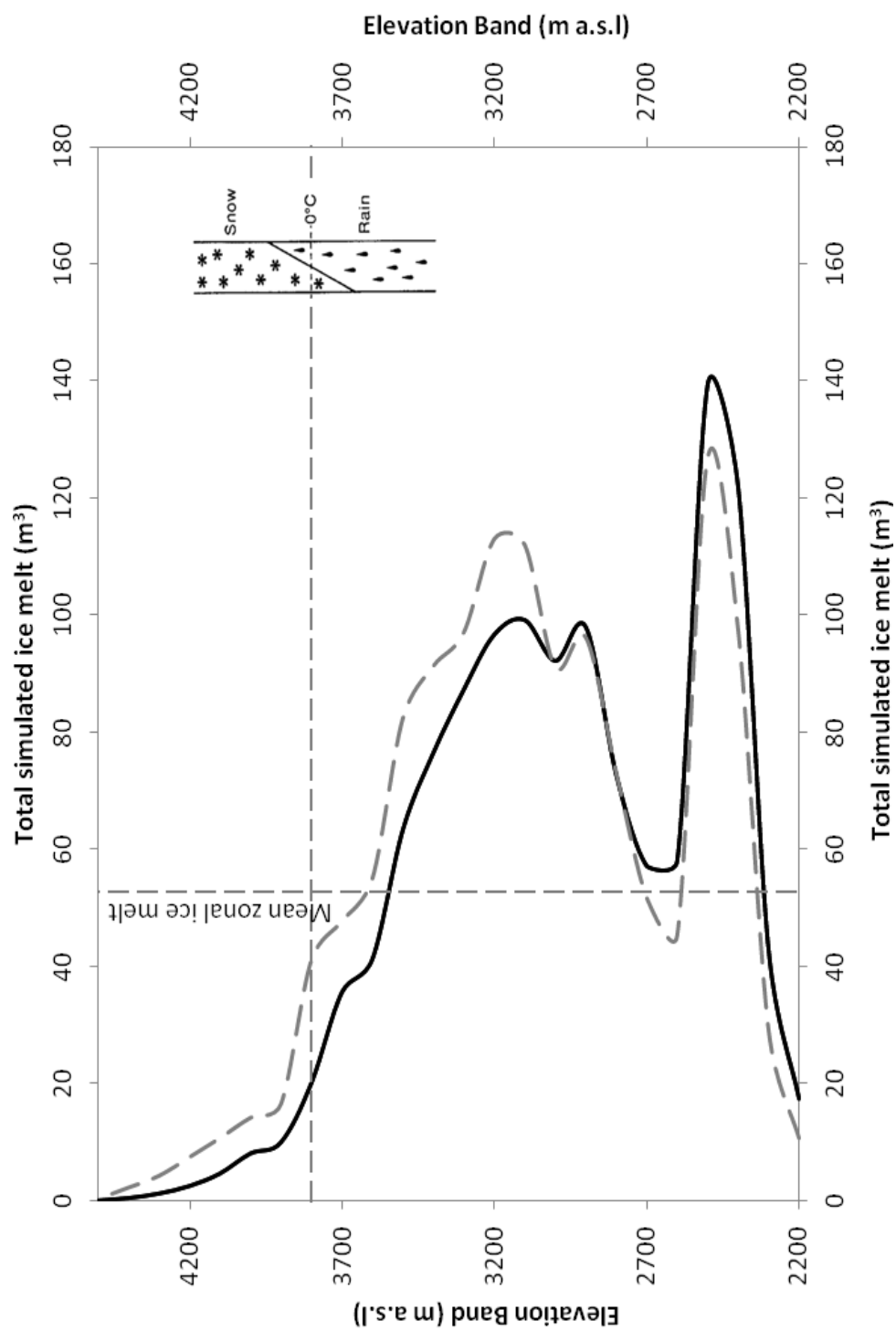
**Figure 4.1.7** Mean daily modelled ice melt (solid line) and +3°C rise model (dashed line) during ablation season 2008 for the basin containing Gornegletscher.

The +1°C model assumes no ice area change, whereas the +2°C and +3°C models do, Therefore, ice melt differs from the original model, and is raised in the +2°C and +3°C models by 21.7% and 5.62% respectively. The models indicate that conditional of increased ice area availability and high mid-summer temperatures, that this will result in high magnitude ice melt.

The 21.7% contribution increase in ice melt in the 2°C model is likely to coincide with the transient snowline being raised by around 160 m/+1°C, resulting in a high fraction of ice melt from mid elevation bands (2900 – 3600 m a.s.l) (fig4.1.8). There is limited difference between the original +1°C model and the +3°C model (fig4.1.9) and this is echoed in the highly elevated bands of the basin with high ice areas. The availability for melt at certain elevations is expected to decrease as ice areas are reduced, and subsequently resulting in less frequent high magnitude periods of ice melt.



**Figure 4.1.8** Modelled total ice melt (Solid line) by elevation band, interaction with 0°C isotherm and band ice melt production in relation to the mean for a +2°C (dashed line) air temperature increase scenario.



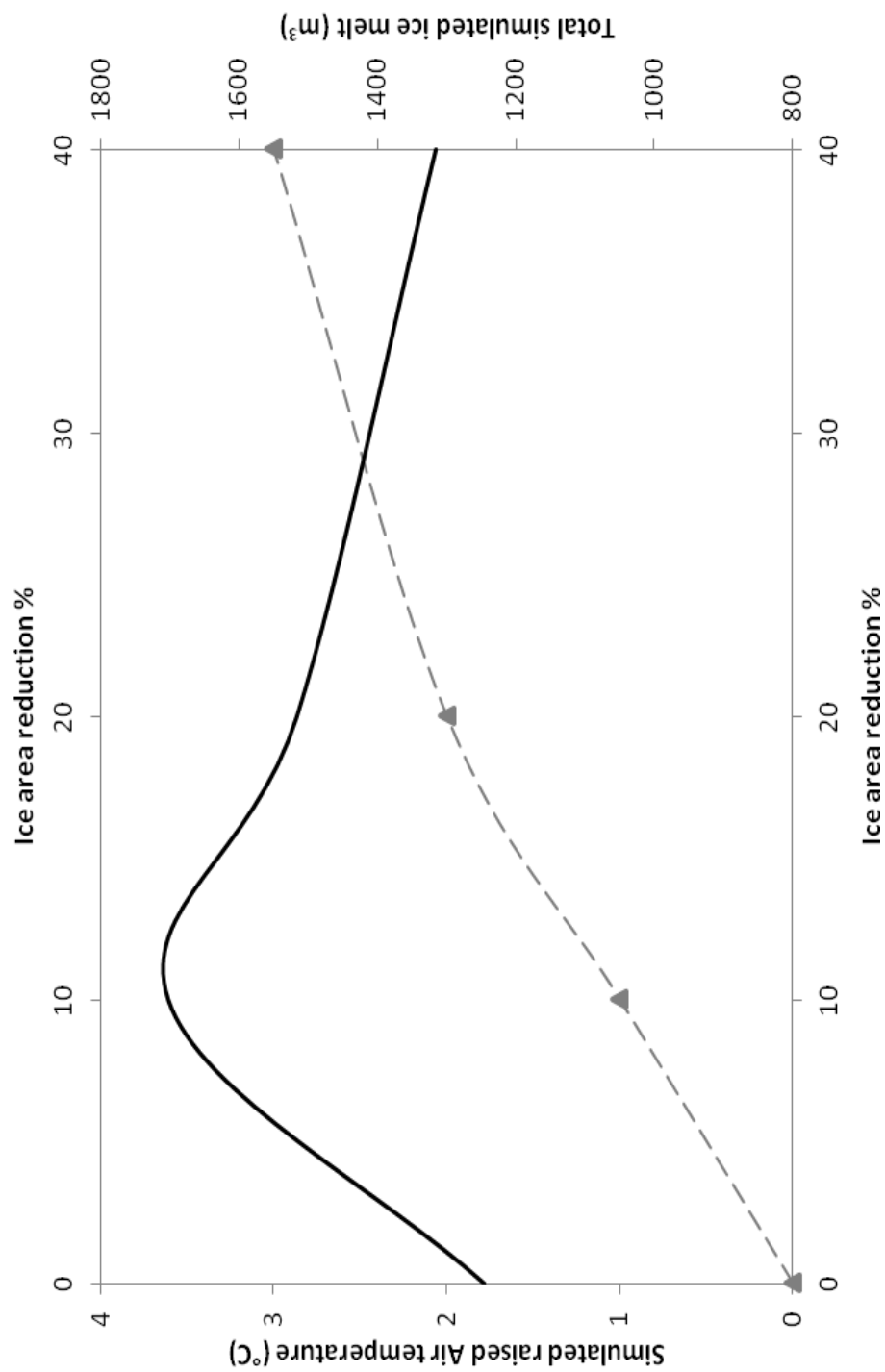
**Figure 4.1.9** Measured total ice melt (Solid line) by elevation band, interaction with 0°C isotherm and band ice melt production in relation to the mean for a +3°C (dashed line) air temperature increase scenario.

The elevation bands 2900 – 3800 m a.s.l have the largest ice areas in the basin, and at these elevations ice melt runoff is increased cumulatively by 32.58% and 17.4% in the 2°C and 3°C models respectively. Reducing ice area by 40% in the 3°C model sufficiently counteracted the effect of ice melt exceeding the original model until 3000 m a.s.l., where it then surpassed due to substantial ice area availability. The 2°C model exceeds original melt simulation at 2700 m a.s.l., and enhanced ice melt at mid – high elevation is a result of further ascent of the transient snowline and therefore progression of mean ice melt runoff.

Ice melt at elevations above the snowline is limited as a result of increased radiation deflection (albedo) by a factor of 0.3 to 0.8, with these areas remaining snow covered, and contribute minimal ice melt to total runoff. The +3°C model (fig4.1.9) indicates some negative change in ice melt at lower elevations until 3000m a.s.l, compared to the +2°C model where ice melt follows the original model until 2700m a.s.l when the +2°C model exceeds the original simulation to 4500 m.a.s.l.

The elevation model computes ice melt differences at 2500 – 2700 m a.s.l from the original model and from the +2°C and +3°C models, yielding ice melt of +5.9% and -12.2% respectively. Given that ice area is reduced in this model by 40%, air temperature is raised by +3°C and a lower ice melt is produced which would suggest glacier wastage. Furthermore, the 2°C and 3°C models advocate that when the maximum snowline position is achieved, and as the snowline ascends runoff is increased as more ice is available at mid elevations, but once ice area is reduced then the model generates reduced runoff values, by comparison with the original model.

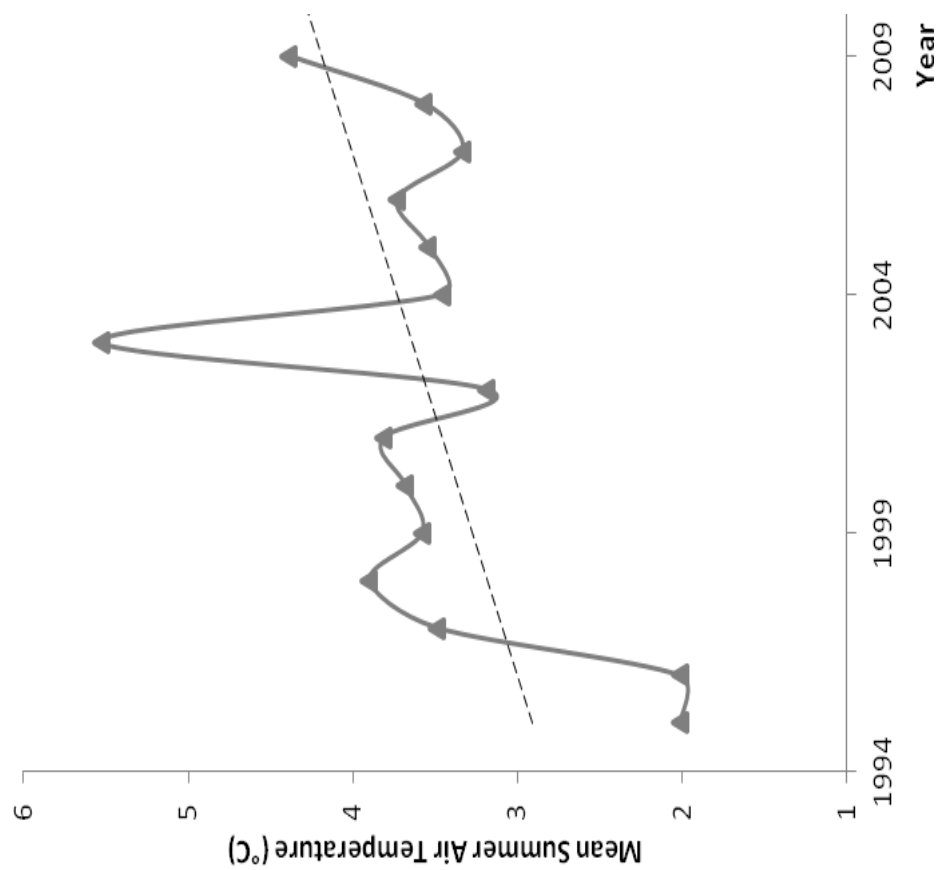
Initially as energy is amplified and ice area is minimally reduced (e.g. +2°C model); discharge is increased due to the ideal conditions created for peak runoff. This is because ice area was reduced by only 20% but air temperature increased by +2°C, so this means there are more frequent degree days at the mid-elevation zones where ice areas are already greatest. (fig4.1.8).



**Figure 4.2.1** Relationship between raised air temperature/reduced ice area (dashed line) and total modelled ice melt (solid line).

As ice area becomes further reduced per  $+1^{\circ}\text{C}$  increase then modelled ice melt depletes. The model suggests that as total simulated melt declines below the air temperature/ice area series (fig 4.2.1), that this becomes the point of ice area depletion. It is unlikely any usual levels of winter precipitation could offset the effects of such ice reduction and summer warming, and this point is identified to be at the stage of 30% ice depletion which is achieved by  $\sim 2.5^{\circ}\text{C}$  air temperature augmentation.

It is expected that over time ice melt runoff from the basin containing Gornergletscher will increase until declining percentage glacierisation results in glacier runoff actually decreasing. This is because mean summer air temperature values between 1995 and 2009 have increased over time, and are expected to continue to rise (fig4.2.2) but the glacier area as yet has not reduced sufficiently to affect total flow.



**Figure 4.2.2** Mean summer air temperature derived from measurements (Gornegrat 3089 m a.s.l.) ;based on data recorded hourly between 1995 and 2009.



Mean summer air temperature for ablation season 2008 the year used in this investigation was 3.57°C. Therefore, in the model an ice area depletion of 30% could result from an enhanced energy availability of +2.5°C in addition to the 3.57°C, resulting in a mean summer air temperature of around 6°C.

Mean summer air temperatures are expected to continually rise, with the likelihood of a strong correlation during summer months between precipitation and runoff from the basin. This will happen following increased temperatures in summer which ultimately reduces ice area. This coupled with higher air temperatures meaning precipitation will more frequently reach the basin and runoff immediately rather than being accumulated as snow/ice. Therefore warm air temperatures and low ice area indicates runoff will become increasingly regulated by precipitation.

The fraction of ice melt contribution to summer runoff is expected to be highly reduced in the coming decades. This is because following the period when ice melt is initially raised to high magnitudes in summer months, then over decadal periods, this will lead to reduced ice areas and continued thinning of Gornergletscher.

## 5. Discussion

Simple climate change models are useful so that climatic variability can be represented by a small number of independent constraints. The temperature index method in this study models ice melt runoff for the basin containing Gornergletscher, driven only by air temperature and ice area data. The degree day factors for ice were found to be between 0.011 – 0.012 mm w.e. °C<sup>-1</sup>, and the lapse rate used was -0.6°C/100m. The models estimated daily ice melt during summer months based on various ice areas, elevation bands, and +1°C, +2°C, +3°C scenarios for climatic change.

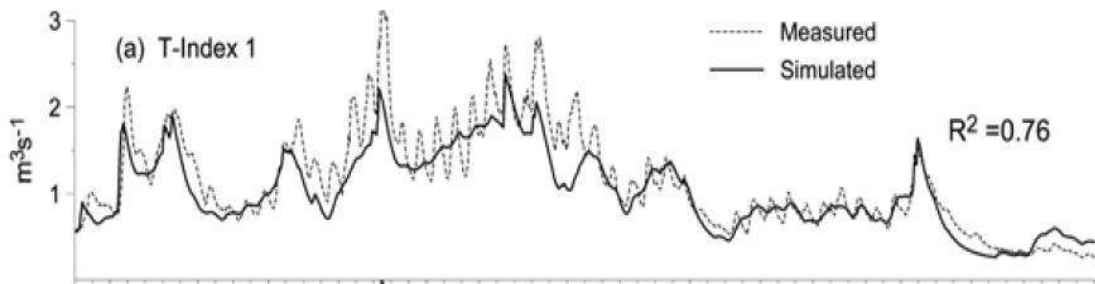
The discussion here is separated into five sections; firstly the findings from the original ice melt model are addressed. Secondly, ice melt runoff by elevation band and the relationship with basin hypsometry and the transient snowline are discussed. The third point addressed is tuning the model to enhanced air temperatures and reduced ice areas. The fourth element relates to the model as a tool, its functionality, accuracy and implementation to estimate glacier response to air temperature fluctuation. Finally, a brief discussion regarding improvements and model development/modification is outlined aiming to highlight future research possibilities and developments of the model.

### 5.0.1 Modelled runoff response for summer 2008

Water is temporarily stored during winter months, and runoff is delayed until summer months when radiation is raised and then air temperature increases. Precipitation and discharge in most glacierised basins have a weak, negative correlation during summer months. This is because high air temperatures release water as snow and ice melt, corresponding with ascent of snowline and ice area exposure.

Modelled mean daily ice melt for Gornergletscher begins relatively low then peaks during late-summer months when maximum radiation is achieved and the transient snowline maximum is reached. Mean daily variations in modelled ice melt are evident, and this is also shown in measured mean runoff measurements. This could be for several reasons, primarily the time resolution of the model which encompasses the most part of the ablation season. Additionally, the scale of the basin containing Gornergletscher and the portion of glacierisation are characterised by large day-to-day

high magnitude flows. This sensitivity to climatic change is represented by frequent peaks and falls. Hock (1999) models runoff for a small low glacierised basin (fig.6.1) containing Storglaciaren, Sweden, and lower daily variation is noticeable.

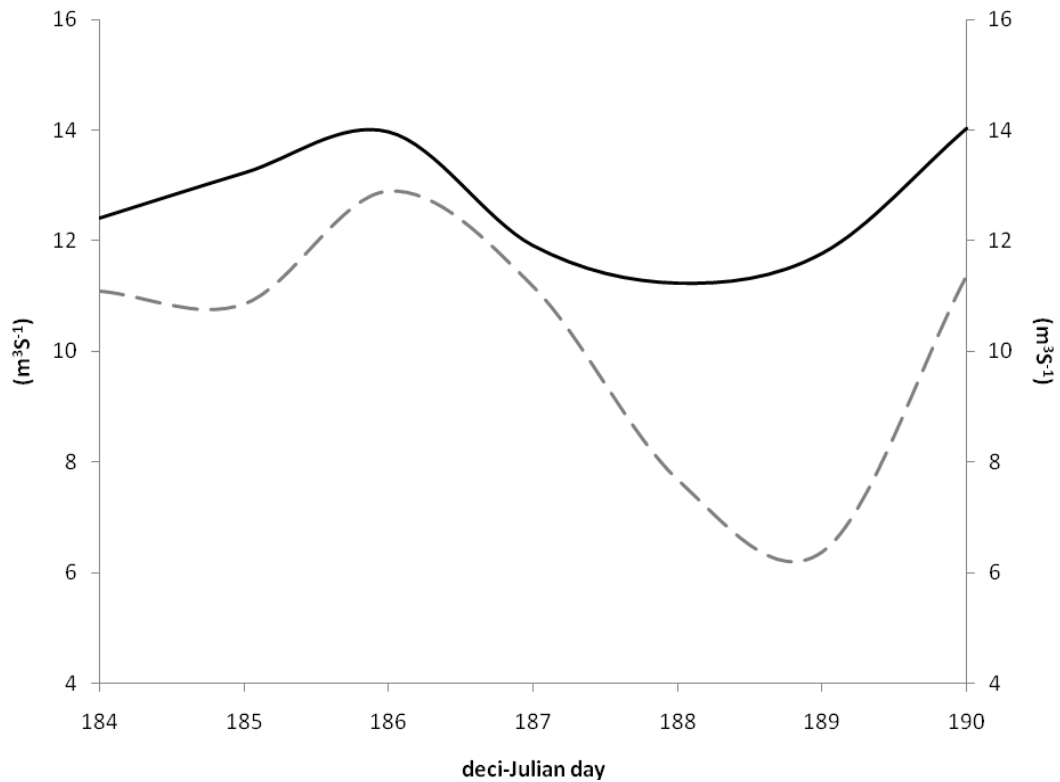


**Figure 5.1** Simulated and measured mean hourly discharge  $Q$  ( $\text{m}^3 \text{s}^{-1}$ ) of Storglaciaren for the period 11 July – 6 September 1994 (Hock 1999).

Modelled runoff for Storglaciaren, Sweden (Hock, 1999), shows similarities to the model in this investigation of runoff from Gornergletscher. This is because the daily curves of response to air temperature are shown in both models, and sometimes there is deviation during peak flow periods, possibly due to time lag of modelled melt and measured melt at the gauge. For a parcel of water flowing from the glacier, transit time is reduced in summer as velocity increases with runoff (Collins 2009). Although, during the ablation season, from the point of melt, a parcel of water can still be in transit to the gauge for more than 24 hours at low volumetric flows. This lag rate has been investigated in a number of studies by using dye tracing methods to effectively measure the transit time from melt to gauge (e.g. Jansson et al. 2002; Nienow et al. 1998)

Modelling ice melt from the classical degree day method yields a good simulation of the seasonal pattern of discharge, but the daily runoff fluctuations are hardly reflected by the model. Hock (1999) uses precipitation and radiation measurements to increase the accuracy in the model to model runoff, whereas the model in this investigation is entirely represented by ice melt runoff. Lang and Braun (1990) recall daily temperature fluctuations are not sufficient to account for the daily cycles in melt water production. Therefore a combination of both temperature index modelling as an estimation, and lapse rate between melt and gauge, represent curves with similar response but with marginal deviations.

Ice melt modelling over a shorter time resolution (fig.6.2) indicates a more accurate relationship between modelled runoff and measured runoff.



**Figure 5.2** Mean diurnal simulated ice melt (dashed line) and measured discharge (solid line) of Gornergletscher during the period 3 July – 9 July.

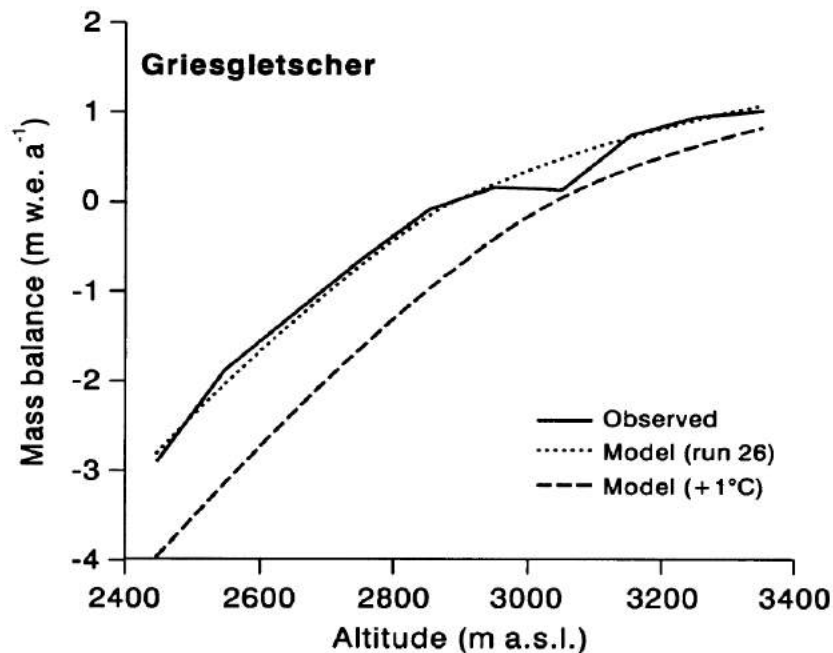
Temperature index modelling summer runoff for a large scale basin increases the accuracy when more input parameters are considered. However, some sources of runoff cannot be accounted for in simulations, such as water storage and release from groundwater, reservoirs, ice marginal lakes and outburst floods. Storage parameters are expected to vary with discharge and over time since the internal glacier drainage system evolves as the melt season progresses (Rothlisberger and Lang 1987).

Between Gornergletscher and Grenzgletscher, the basin contains an ice marginal lake - Gornersee. The lake usually starts to fill in May and drains annually between June and August. Each year  $1 - 5 \times 10^6 \text{ m}^3$  of meltwater are contained by the lake, and typically fills to the maximum level beyond which outflow occurs at the start of the drainage (Huss et al 2007). Drainage of Gornersee would explain the large peak in measured runoff during the period day 190 – 205, and the regular daily regime is maintained by simulated ice melt during this period.

Ice melt runoff from the basin containing Gornergletscher was modelled by tuning air temperature by  $+1^{\circ}\text{C}$ , and was tuned to assess the response of ice melt and found a rise of 24.8%. The tuned model is always expected to increase ice melt from a glacierised basin, and the scale of daily ice melt fluctuations would also be enhanced. Daily runoff fluctuation will, at least in an initial phase, be amplified by enhanced daily air temperature and more efficient water transport through the glacier (Braun et al 2000). Irregular ice melt runoff becomes more frequent following raised air temperatures in the  $+2^{\circ}\text{C}$  and the  $+3^{\circ}\text{C}$  model, because the dynamics of glacier storage, water transit and conduit system are altered, and therefore the daily runoff magnitude peaks higher and falls lower.

As a result of enhanced air temperature, ice melt runoff in the model reflects raised energy availability and higher radiation absorbance at high elevation bands. If in reality, air temperatures were raised to the extents used in these models, then increased runoff could not be maintained by Gornergletscher in the longer term e.g. over the next 100 years. Furthermore, winter accumulation is likely to be insufficient to offset warming on a  $1^{\circ}\text{C}$  scale. Initially, runoff is greatly enhanced due to higher air temperatures, but with decreasing ice area the water yield will gradually reduce or be fed mainly by precipitation. Once ice area declines then summer runoff is greatly reduced (Hock and Jansson 2005).

The model was forced to indicate responses to air temperature increase scenarios of  $+1^{\circ}\text{C}$ ,  $+2^{\circ}\text{C}$ ,  $+3^{\circ}\text{C}$ , and the runoff showed increased ice melt runoff. In comparison Braithwaite and Zhang (2000) used a degree day model to investigate the mass balance response of Griesgletscher, Switzerland to a  $+1^{\circ}\text{C}$  air temperature by elevation band (fig.5.3) in order to investigate the relationship between air temperature, and ablation.



**Figure 5.3** Modelled mass balance for Griesgletscher for present climate and for a  $+1^{\circ}\text{C}$  temperature rise (Braithwaite and Zhang (2000)).

The clear change in the model (Braithwaite and Zhang, 2000), is a loss of  $> 1 \text{ m w. e. a}^{-1}$  across the glacier between 2450 and 2900 m a.s.l subsequent of  $+1^{\circ}\text{C}$  temperature rise, with a progressively smaller increase with altitude, because where there is high precipitation there is also reduced melting (at high elevations) and therefore a lower sensitivity to increased heat energy (Braithwaite and Zhang, 2000). The tuned degree day model for measuring mass balance at Griesgletscher found a  $+1^{\circ}\text{C}$  temperature increase would reduce mass balance by an average of  $0.69 \text{ m w.e. a}^{-1} \text{ }^{\circ}\text{C}^{-1}$  and  $1 \text{ m w.e. a}^{-1} \text{ }^{\circ}\text{C}^{-1}$  at the terminus.

The results of the Braithwaite and Zhang (2000) investigation are in agreement with the findings of this study regarding glacierised basin spatial sensitivity. At 2600 m a.s.l. ice area ablation is highest, and melting only becomes reduced at altitudes above the transient snowline maximum, hence variation in the spatial mass balance values,

controlled by the level of precipitation and air temperature. It is expected as the glacier terminus; being most sensitive, is melted then the overall sensitivity of the remaining part of the glacier would be reduced. Braithwaite and Zhang (2000) propose the strong relation between sensitivity and elevation suggests climate/glacier ablation studies should be performed for individual elevation zones rather than for whole glaciers.

The magnitude of modelled runoff is relatively low during early summer for the basin containing Gornergletscher following model tuning. Ice area availability is typically low during May at lower elevations where ice area exposure is comparatively limited during this period of summer; radiation absorbance is still largely controlled by the reflective properties of snow. Tuned air temperature can be disproportionately reflected in runoff volumes following melting of the seasonal snow pack in early summer and initial snowline ascent.

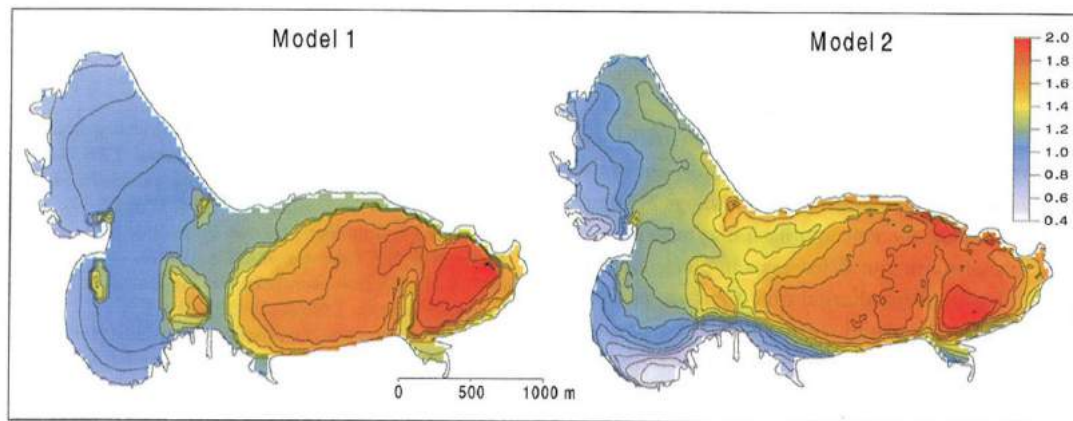
Summer runoff increases from both raised air temperatures and percentage glacierisation by the amount of ice area available to absorb increased radiation. In the long term, runoff could correlate positively with precipitation rather than air temperature as the quantity of ice in the basin decreases. However initially, the correlation between air temperature and runoff is expected to increase whilst there are still large ice areas available for melt at mid elevations (Hock and Jansson 2005). Similar to early summer months, reduced glacierisation over time will in the initial stage generate increased runoff, although ultimately melt runoff is controlled by ice area. Therefore the lower percentage glacierisation available for melt, then the less influence air temperature has on runoff from the basin.

#### 5.0.2 Modelled runoff response for elevation bands

Modelled ice melt for the basin containing Gornergletscher showed that the elevation band 2500 – 2600 m a.s.l generated most ice melt during summer 2008. This elevation band has the greatest ice area below 3100 m a.s.l. and experienced c. 100 positive degree days during the study period out of the possible 116 day time scale. Area distribution of the elevation band is second highest of the basin until 3100 m a.s.l. This suggests a wide, flat distribution of ice at 2500 – 2600 m a.s.l. Ice area of

this elevation zone encompasses 54.6% of total basin area distribution; coincidentally the tributaries feeding the main system connect to Gornergletscher at 2500 – 2600m a.s.l.

Hock (1999) models two temperature index distribution models (fig.5.4), using the classical degree day factor approach (model 1), and including potential clear sky solar radiation (Model 2) in order to simulate spatial melt from Storglaciaren, Sweden.



**Figure 5.4** Simulated cumulative areal meltwater equivalent (m) of Storglaciaren, 5 July - 25 August 1994, using models 1 and 2. Areas of increased melt correspond to the areas where ice is exposed (Hock 1999).

The distributed temperature index model shows spatial ice melt becomes more accurate by utilising potential clear sky radiation rates rather than solely using a temperature lapse rate over elevation. The simulation created for Storglaciaren clearly shows greatest ice loss is experienced at lowest elevation, typically around the terminus. This is a result of ice area distribution for the basin containing Storglaciaren and is based on ice area exposure. The hypsometry of Gornergletscher and being a wide, flat glacier, then ice melt does not necessarily increase uniformly across the basin.

Furthermore, modelled runoff for the basin containing Gornergletscher is greatest at the elevation band where tributary glaciers connect to the main system. These confluent systems are expected to endure more rapid ice loss than trunk Gornergletscher, both seasonally and over longer periods, resulting from their elevation zone distribution.



The tributaries are characteristically narrow and have concentrated ice masses, and their sensitivity to increased air temperatures is greater than the main trunk of Gornergletscher. Tributary ice areas are generally concentrated and join the trunk glacier body at low to mid elevations. Therefore during periods of climate warming these tributaries generally retreat first, contributing to runoff and eventually disconnecting from the glacier.

Modelled runoff by elevation from Gornergletscher represented ice melt in a uniform trend, which would not be expected to correspond with the basin hypsometry of Gornergletscher. Although elevation band runoff values are accurate, a higher spatial resolution could be achieved with radiation data due to topography variation of Gornergletscher. Vincent and Six (2013) highlight the role of potential solar radiation in determining the spatial variation of cumulative ice loss. They conclude that the spatial variation of melt is mainly driven by potential solar radiation, and changes in ice melt were analysed over time using temperature and solar radiation data. Carenzo et al (2009) found strong variations at altitude in temperature factors on Haut Glacier d'Arolla, Switzerland, but found a stable radiation factor whatever the melting season or investigated area. As a result, the investigation obtained very effective model performances over a wide range of surface and meteorological conditions with an averaged temperature factor. It is evident the runoff model for Gornergletscher would have performed with higher accuracy if potential clear sky radiation data had been made available and introduced to the model.

Ice melt runoff, and simulation of the process is directly controlled by air temperature, which in turn is regulated by radiation levels. Many aspects of glacierised basins influence the control of radiation on melting through air temperature. The investigation in this study simulates approximate values of melt rates based on parameters which strongly correlate with summer runoff from a highly glacierised basin.

Highest ice area distribution at 2500 - 2600 m a.s.l comprises a large portion of the glacier, and ice area at this band is subject to thinning as a result of the wide, flat dimensions of the main body. 2500 – 2600m a.s.l is the elevation at which the tributaries connect to the main system, subsequent of enhanced warming of around

+1°C would reduce tributary extent, and induce partial detachment from trunk Gornergletscher.

The tuned model increasing by +1°C suggests the greatest increased change of ice melt is at 3100 – 3200 m a.s.l. At this elevation zone, ice melt is increased by 35.6% with the enhanced energy availability. Ice melt for the elevation band (2500 – 2600 m a.s.l.) at which the tributaries connect to Gornergletscher is amplified by 23.8%, and tributary length would be expected to reduce in proportion to their mass and extent over elevation bands.

The main system of Gornergletscher reduces in volume by thinning first and then retreat, during which it is possible sections of the main glacier trunk could disconnect from the more highly-elevated areas of the basin. Braithwaite and Zhang (2000) found greatest ice loss is experienced at the terminus in their modified air temperature model of Griesgletscher. They utilised a temperature index model to assess mass balance, and their study discovered a 20% precipitation increase could partly offset the increased ablation caused by a 1°C rise in air temperature but could not compensate for it. With reference to the Gornergletscher model where greatest ice melt was experienced at 2500 to 2600m a.s.l, it is unlikely a 20% increase in precipitation would significantly affect ablation rates, and would more likely just contribute to increased runoff. Albeit the increased precipitation could delay the snowline transit, reducing the time ice surface is exposed to high levels of radiation.

The sensitivity of Gornergletscher to increased energy availability can be gauged by tributary retreat. The tributaries connecting to the main system retreat to higher elevations, where there is increased precipitation and a reduced sensitivity to air temperature. Braithwaite and Zhang (2000) recall the sensitivities found for five Swiss study glaciers i.e. -0.7 to -0.9 m w.e. a<sup>-1</sup> °C<sup>-1</sup>; these results most likely represent an intermediate range in global terms, with lower values for sub-polar and high altitude glaciers and higher values for very maritime glaciers (Oerlemans and Fortuin 1992). It would be expected ice loss from Gornergletscher would be approximately twice the values found by Braithwaite and Zhang (2000) at c. -2m w.e.a<sup>-1</sup> °C<sup>-1</sup>. This is because overall modelled melt runoff by elevation of Gornergletscher (compared to

Griesgletcher) suggests with the energy available and ice area at lower altitudes would induce high magnitude runoff, resulting in increased ice area loss.

### 5.0.3 Modelled runoff response by tuning air temperature and ice area

The magnitude of ice melt runoff is raised significantly in the +2°C model as a result of increased heat energy for melting of ice covered portions in the basin, which are minimally reduced by 20%. It is thought this scenario would be similar to any initial phase of high magnitude runoff following climatic change. An initial phase of high runoff would be experienced after warming of +2°C as ice area is still relatively high, and with ascent of the transient snowline of ~160m/1°C, revealing more ice for melt.

However, Ice melt patterns in the +3°C model change negatively from the original simulation, suggesting ice loss in the basin. Given that increased warming of +3°C, then it would be expected large amounts of runoff would drain the basin from primarily high elevations (Braithwaite 2008). Of course, high levels of warming do not directly imply glacier wastage, but reduced ice area (by 40%) in the +3°C model indicates the effect of melt from a depleted ice covered basin. If glacier mass balance is negative, then glacier wastage is defined as the volume of ice melt that exceeds the water equivalent of the annual volume of snow accumulation in to the glacier system, causing an annual net loss of glacier volume (Comeau et al 2009). Furthermore, In Switzerland, glaciers lost around 18% of their area from 1985 to 1998/99 (from 1973 to 1985 the change is only -1%). This corresponds to an average relative area loss of 14% per decade, which is about seven times higher than the decadal loss rate between 1850 and 1973 (-2.2%) (Paul et al 2007). Given Gornergletscher is a wide, flat glacier then its negative volume could be subject to down-wasting, as a result of its inability to retreat to high elevation.

The global linear trend of retreating glaciers, identified by rapid decrease of ice area indicates that glaciers were not able to primarily adjust to the current climatic conditions by a dynamic retreat towards higher elevations with cooler temperatures (Haeberli and Hoelzle 1995). Instead the reduction in driving stress and flow facilitates down-wasting which even results in elevation lowering of the glacier surface. Glacier wastage as a result of high magnitude summer ablation is highly

influenced by albedo in the Swiss Alps. Therefore not surprising that ice melt significantly lowers when ice area is depleted by 40%, hence the weakened influence of albedo in a partially ice covered basin.

Glacier albedo exerts a major influence on the energy balance (e.g. Klok and Oerlemans, 2002; Paul et al., 2005) and therefore on the summer ablation, which governs the variability of the annual balance for most glaciers (Oerlemans and Reichert, 2000). The decreasing glacier albedo is also part of a positive feedback that enhances glacier melt even more in the short term. The influence of albedo and ice melt in the basin containing Gornergletscher would be expected to diminish with ice area reduction over the coming decades. Modelled tuned air temperature and the effects on basin dynamics in the Swiss Alps are outlined by Paul et al (2007); e.g. growing regions with rock outcrops, separation from tributaries, formation of pro-glacial lakes, all of which related to positive feedbacks, which will further accelerate glacier disintegration over the next two decades.

#### 5.0.4 Performance of the Runoff Response Model

Modelled runoff draining the basin containing Gornergletscher required a temperature index model which used a degree day factor of 11.5 (Lang 1986 and Hock 2003), and assumed a temperature lapse rate of 0.6°C/100m (Quick and Pipes 1977). Ice melt runoff was modelled for several scenarios to investigate sensitivity of the glacierised portions in the basin to temperature patterns and fluctuation. The model investigated; ice melt simulation for ablation season 2008; runoff response to a +1°C, +2°C, +3°C air temperature tuning, and the melt contribution from each elevation basin in the basin, and the elevations that respond most to air temperature tuning.

The method used was effective to model individual components (e.g. ice melt) of total runoff draining a glacierised basin; this approach is based on strong regression coefficients between air temperature and runoff. Braithwaite and Olesen (1989) found a correlation coefficient of 0.96 between annual ice ablation and positive air temperature sums. Since air temperature generally is the most readily available data, such models have been the most widely used method of ice and snow melt

computations for many purposes, such as hydrological modelling, ice dynamic modelling or climate sensitivity studies (Hock, 2003). This is because glacierised basins store water as ice and delay runoff until albedo is lowered and sufficient energy becomes available for melt (in summer), and air temperature is raised during summer months which is reflected in enhanced ice melt runoff from the basin.

Modelling runoff response was performed by a uniform calculation method across the basin, and although an accurate representation of ice melt is generated, it is widely cited in previous literature that long wave radiation can improve model precision several-fold. The reason for the success of air temperature as the sole index of melt modelling, (despite the predominance of net radiation as a source of melt energy), is attributed to the high correlation of temperature with several energy balance components.

The spatial distribution of energy for melt and degree day factor variability, across highly glacierised large basins, can reduce the correlation coefficient for a uniform temperature index model, and it is for this reason radiation enhances model performance. Hock (2003) suggests that typically the role of longwave radiation is by far the most important heat source for melt and together with sensible heat flux provide ~75% of the entire energy source for melt. Both heat fluxes are highly affected by air temperature which provides the main reason for the strong relationship between melt and air temperature.

In order to overcome this issue in temperature index modelling, and increase model accuracy, Hock (1999) proposes, allowing the degree day factor to vary according to potential direct solar radiation permits both a better simulation of daily melt cycles and accurate modelling of the spatial variability of melt rates in complex topography. For that reason, using direct solar radiation in the model would improve the spatial representation of melt rates for runoff modelling since melt rates are affected by basin hypsometry.

Modelled runoff by elevation zone shows a strong relationship with basin hypsometry by elevation band, and ice area within each band. The frequency of positive degree days and the amount of heat available coupled with basin hypsometry at each

elevation band determines the scale of spatial runoff during summer. However, temperature-index runoff models, and spatial melt runoff across the basin are generally considered a crude representation in basic runoff models, despite elevation bands and lapse rates often being the only criterion for defining spatial boundaries, also melt rates will only vary as a function of elevation resulting from an air temperature lapse rate.

The elevation band runoff model used for the basin containing Gornergletscher generated expected results, because ice melt runoff was typically greatest from elevation bands with high areas, and ice distribution at mid-elevations. To account for variation of melt by elevation, when using a spatially constant degree-day factor, melt-runoff models often divide the basin into elevation bands to consider a decrease in melt with increasing elevation, or divide into aspect classes to account for enhanced melt on e.g. south-facing slopes compared to north-facing slopes (Hock 2005). The spatial distribution of melt rates are accounted for in a coarse, uniform method which produces sufficient results based on ice areas which control the quantity of melt.

However, several aspects of heat flux and exchange at the glacier surface are not accounted for in the investigation of Gornergletscher, and elements of energy transference and fluctuation across the large basin containing Gornergletscher are input to the model included in the degree day factor. Furthermore, the spatial variation of melt rates across a glacier can only be modelled through changes in elevation associated with the air-temperature lapse rate.

In reality, spatial melt-rate variations are due to variations in the surface energy balance from location to location, and are controlled in a complex way by topographic features and surface conditions, principally surface roughness and albedo (Pellicciotti et al. 2005). The model accuracy of ice melt from Gornergletscher would certainly improve following data input of long wave radiation and albedo distribution measurements across the basin. Conversely, additional data input to a temperature index model would surely indicate moving towards utilising an energy balance method and hinder the simplicity of a temperature-index model.

Energy balance modelling is arguably more suitable for modelling spatial distribution of ice melt, although enhanced temperature index models are commonly employed. The model Hock (1999) uses is a simple temperature-index method which alters the degree-day factor spatially and temporally as a function of a potential radiation, dependent only to topography and solar geometry, but is still compatible with the data requirements of a simple temperature-index model. However, when shortwave radiation data are available, a more physical representation of melt, based on the energy-balance equation, seems more appropriate to the formulation of the spatial model originally formed. The melt model for Gornergletscher represents a fairly accurate, uniform runoff model; because the response of ice melt when to tuned air temperature by elevation in the model yielded expected results, as did runoff model over time once it had been tuned.

An important question when modelling runoff is whether model parameters determined from the current climate can be used to predict changes associated with a different climate e.g. future decades. This issue queries model tuning to air temperature scenarios, because raised mean air temperatures of  $+1^{\circ}\text{C}$  would result in high runoff, however the time period before the  $+1^{\circ}\text{C}$  is achieved it would be assumed ice area would decrease, and therefore the correlation coefficient becomes weaker between air temperature and runoff from the glacierised basin. Furthermore it is not thought that air temperature would increase to  $+1^{\circ}\text{C}$  instantly from one summer to the next. Therefore, a gradual air temperature rise would deplete ice area over time and by the time  $+1^{\circ}\text{C}$ , the ice area of 2008 would not correspond to future ice area coverage.

#### 5.0.5 Model Improvements and Future Research

The runoff model from the basin containing Gornergletscher is simplistic but achieves fairly correct results (3.96% difference in total summer runoff) in relation to the parameters used. Model performance is relatively coarse. However when calibrated with measured runoff over time and changing the degree day model shows a high level of consistency and accuracy. Gornergletscher is a large basin with high glacierisation and unusual hypsometry. Therefore it would be prudent for effective and accurate modelling that future studies should take in to account two essential

components; (i) the variability of DDFs at different basin locations, i.e. ablation magnitude differs at 2200 m a.s.l and 3500 m a.s.l. (ii) long wave radiation data or potential clear sky radiation input to the model to improve energy transference at different ice portions of the basin would arguably be the most controlling aspect of heating at the glacier surface. This would ‘smooth out’ any weak correlation events between air temperature and runoff, i.e. daily precipitation may offset the influence of air temperature, and this is not the case with radiation data.

Modelled runoff from different elevation bands are not previously accounted for in temperature-index runoff models, but mainly simulated by energy balance models. This type of spatial modelling, for greater precision, requires calibration of results with mass balance measurements. However mass balance data is considered a scarce, limited data source (Huss 2012, 2013 and Zemp et al. 2009). The remote, inaccessible environments of glaciers restrict surface data collection, hence spatial modelling investigation inadequacy and the constraint to only very few study basins. While previous research has focussed on the impact of climate change on glacier mass balance (Joannesson and Laumann 1993, Braithwaite and Zhang 1999) and glacier size variations (Oerlemans 1994), far less attention has been paid to the effects on glacier runoff (Hock and Jansson 2005). The features of glacier runoff and their significance for catchment runoff have long been documented, however few studies have attempted to quantify the response of tuned air temperature and ice area on glacier runoff using numerical models (Braun et al. 2000).

Modelling runoff response of ice melt, could be critical in coming years in order to prepare for irregular runoff regimes, and further in the future the depletion of basin ice. Elevation band contribution to runoff, calibrated with altitude mass balance measurements would provide information on glacier ice loss areas.



## 6. Conclusions

There is generally a relation between the melting of snow and ice and air temperature which can be modelled using degree-day methods. No doubt the relative advantages of degree-day and energy-balance methods will continue to be examined, however a greater quantity of climate data from glaciers in different climatic regions are required to effectively use model tuning. Modelling runoff for the basin containing Gornergletscher during ablation season 2008, which used a classical temperature-index approach, yielded a reasonable agreement between modelled and measured runoff.

Model calibration may not have correlated precisely due to the additional variables contributing to runoff during summer months e.g. summer precipitation, groundwater, and snowmelt, all of which are reflected in measured runoff but not in the model. However, the daily pattern typically represented by measured runoff was followed by modelled runoff, even though a lag time between modelled and measured runoff is apparent. The lag time is a result of the model accounting for melt immediately as air temperature changes in real time. Realistically, from the point of melt to measurement at the gauge a parcel of melt could experience a transit time of around 24 hours.

Modelled runoff by elevation was a suitable method to simulate runoff from different areas across the basin; and the uniformed approach achieved fair results which were initially hypothesised. However, to introduce greater accuracy to the spatial model, then additional data are required e.g. clear sky radiation; variation of DDFs over the basin. The capacity to vary a degree day factor by elevation, long wave radiation/potential clear sky radiation and albedo would generate a more defined/accurate model. Additionally, as Hock (1999) suggests that the topographic effects on melt of slope, aspect and shading are not measured, yielding an unrealistic areal distribution of melt rates in complex terrain. However, the lack of data availability to perform this implies that such parameters were ‘lumped’ in to the simulation through the DDF (Braithwaite 1995).

### 6.0.1 Modelled Runoff for summer 2008

Firstly, this investigation aimed to produce a basic temperature index model able to model runoff for the summer of 2008. The ability to generate a model from ice area and air temperature data for a glacierised basin, coupled with an assumed lapse rate and degree day factor could be used to model runoff from other glaciers within basins of unusual hypsometry. The Lapse rate used is generally homogenous for most Alpine mountain glaciers, and regional air temperature data is widely available, leaving ice areas from satellite imagery to be obtained.

Ice area is calculated from remotely sensed imagery which is easily accessed and widely available at low cost, and degree day factors are deduced from previous studies and using trial methods to find which follows measured runoff. Although it is now recognised these factors vary in time and space (Braun et al 1994, Hock 1999), therefore achieving a degree day factor or several which are independent to each investigation.

Daily modelled runoff during initial summer months began at a relatively low level and was later raised around day 175 for the duration of summer. Modelled runoff is low during May, and is expected as the seasonal snowpack is still being melted (Lang and Braun 1990 and Pellicciotti et al 2005), accounts and contributes the main fraction to runoff from basin during May. Actual discharge follows the pattern of simulated ice melt fairly well, specifically during early to mid-summer months, from day 127 - 190. Furthermore, since the original runoff model draining Gornergletscher accounts for limited parameters, the daily regime of measured runoff is relatively well-followed.

### 6.0.2 Modelled runoff by elevation band

The second purpose of this investigation was to model runoff by elevation band for the basin containing Gornergletscher. The reason for this was to identify areas of the glacierised basin that respond differently to changing air temperature values. It was initially expected in the investigation design that runoff would progressively decrease after an initial phase of high magnitude ice melt, and for melt to remain linear with elevation as a result of the lapse rate with altitude ascent. Nonetheless, ice melt runoff is rapidly increased between bands 2300 – 2800 m a.s.l, whilst band 2500 – 2600 m

a.s.l produces most ice melt throughout the total glacier, ice melt is then reduced between 2600 – 2800 m a.s.l. Then a phase of maintained raised ice melt over a greater area is then achieved between 2800 – 3500 m a.s.l, these combined zones contribute 55.02% of overall ice melt from Gornergletscher.

Basin hypsometry was found to play a significant role in modelled runoff by elevation (Braun et al 1993 and Hock 1999). The elevation bands with greater area distribution typically have greater ice areas, and should such bands become below the transient snowline, then this could begin the initial phases of high magnitude summer runoff. As reviewed earlier in the investigation, this spatial model would benefit from long wave radiation data, which would clarify air temperature measurements. Although, for a fundamental model intending to estimate spatial ice runoff, this study provides a fair simulation. The Gornergletscher contribution runoff model could be further modified to spatially represent the effect on ice melt rates, as a result of basin hypsometry, and the response of tributaries to such changes.

Modelled runoff was tuned to increased air temperatures to model the response of ice area melt from the glacier, and increased heat energy by  $+1^{\circ}\text{C}$  was expected to amplify ice melt runoff on a daily scale, and equally in uniform fashion throughout summer months. However, it was found that the extra quantity of melt produced when air temperature is raised, is dependent on the daily magnitude of original modelled melt (e.g. Braithwaite and Zhang 2000). The results show during mid-summer, when peak radiation levels are achieved (e.g. Johannesson et al 1993), and daily runoff rarely descends below  $5 \text{ m}^3\text{s}^{-1}$  then any additional energy further increases the difference between original and  $+1^{\circ}\text{C}$  model. In reality, this would be the expected result from increasing air temperature during summer. As a result more frequent positive degree days, a greater ice area becomes available (e.g. Hock 2003 and Zhang et al 2006), because the quantity of runoff increased several-fold with each air temperature tuning increment.

### 6.0.3 Runoff response to model tuning

This investigation modelled ice melt runoff by tuning a  $+1^{\circ}\text{C}$ ,  $+2^{\circ}\text{C}$ ,  $+3^{\circ}\text{C}$  rise in air temperature for the basin containing Gornergletscher; the reason for this model was to

identify and assess areas of greatest ice melt in the basin. 2500 – 2600m a.s.l produces the greatest portion of ice melt, which is thought to be due to basin hypsometry and the quantity of ice area within the band.

Furthermore, ice melt is increased most at 3100 – 3200 m a.s.l following a +1°C rise in air temperature, and ice melt is enhanced at 3100 – 3200 m a.s.l by 35.6% following a +1°C rise in air temperature, which is the greatest difference of any other band. This result was not hypothesised and appears to be a relatively rapid rate of ice melt increase following model tuning. This is a mid-elevation band in the basin, and could undergo an accelerated rate of thinning from +1°C scenario.

Moreover, such ice melt at an elevation of 3100 – 3200 m a.s.l would be thought to result in detachment between low and high elevation bands of Gornergletscher. It is unlikely at mid elevation bands that even highly increased precipitation could compensate for the effects of a +1°C air temperature increase (e.g. Braithwaite and Zhang 2000), and not only from immediate ice melt but future ice area/mass loss.

This paper suggests, from the findings of this investigation, that mass balance modelling or measurements undertaken for the basin containing Gornergletscher, specifically at 2500 – 2600 m a.s.l and 3100 – 3200 m a.s.l could aid research for hydrological and hydro-electrical beneficiaries, and in-turn model the response of basin hypsometry to a warming climate.

#### 6.0.4 Summary

Temperature index models are widely used due to a limited number of on-site measurements undertaken, as a result of the inaccessible nature of glacierised basin environments. The study purpose was to investigate modelled runoff over time and from elevation bands, with additional air temperature tuning for the basin containing Gornergletscher. Previous literature was considered and acknowledged in order to determine areas of the basin containing Gornergletscher subject to spatially accelerated melt rates by model tuning. It was found that the areas at which tributaries connect to the main body, at 2500 – 2600 m a.s.l, provided greatest melt runoff quantities by a fair difference from other elevation bands.

The model was tuned to increased air temperatures in order to assess the response of ice melt over summer 2008 and at elevation bands. Previous studies have considered air temperature tuning to model runoff response for day/month time scales (Braithwaite and Zhang 2000), however this study intended to find areas in the basin ice melt is greatest, following increases heat energy. It was found, that following further ascent of the transient snowline, elevation bands characterised by large ice areas become available to melt during a period of high radiation, coinciding with a greater radiation absorbance.

Greatest ice melt runoff after modifying the model is experienced between 2900 – 3300m a.s.l, and mean ice melt across these zones is enhanced by around 30%. The capacity for an elevation band to produce increased ice melt following tuning depends mainly on ice area already present at that elevation and basin hypsometry. Another band to represent a scaled change is 2500 – 2600 m a.s.l, hence tributary contribution to ice area at this altitude. Runoff from other bands (below 3300 m a.s.l), show limited difference after air temperature tuning, and are likely to rapidly correlate with precipitation, more so than air temperature following enhanced energy availability.

Summer runoff is found to significantly reduce when a 30% ice area depletion is tuned in the model from measurements taken in 2008, and therefore an additional +2.5°C increase to the 2008 mean summer air temperature, would, if maintained year to year ensure rapid glacier wasting (Paul et al 2007) of ice covered portions in the basin containing Gornergletscher. Swiss Alpine glaciers lost about 18% of their area from 1985 to 1998/99 (from 1973 to 1985 the change is only –1%). This corresponds to an average relative area loss of 14% per decade, which is about seven times higher than the decadal loss rate between 1850 and 1973 (–2.2%) (Paul et al 2004). This study infers that ice loss for the basin containing Gornergletscher could diminish by 30% by 2035.

The results from this investigation closely correspond with the research of Paul et al (2004) that conclude ice area loss of 14% per decade, and this study identifies a 30% loss during the next 22 year period (15%/11 years). However, this paper suggests ice area loss could be accelerated at a certain point of warming, and this rate of loss will increase over the same time scale. This investigation projects available energy for

melt to develop at a rate of  $\sim 0.7^{\circ}\text{C} - 0.8^{\circ}\text{C}/10$  years until 2035; beyond this time scale, year to year ice loss will be reflected in reduced summer ice melt values for runoff draining the basin containing Gornergletscher.

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